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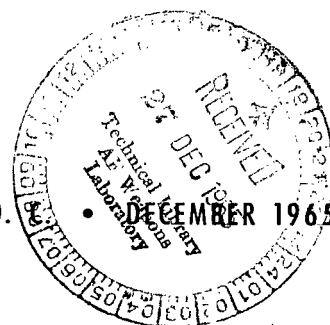
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D.





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SUMMARY

An analytical model is presented for predicting the transient one-dimensional thermal performance of a charring-ablator heat-protection system when exposed to a hyperthermal environment. The heat-protection system is considered to consist of an ablation material and backup structure. The ablating material is further considered to consist of three distinct regions or zones: char, reacting, and virgin material.

A FORTRAN IV digital computer program (STAB II) utilizing an implicit finite difference formulation has been written for the IBM 7094/40 computer system. The program considers one ablating material and a maximum of 12 backup materials with conduction or radiation and/or convection allowed between materials. Thermal properties of all materials are temperature dependent, with the properties of the charring material also being state dependent.

The governing differential equations and their implicit finite difference formulation are presented. The program input and output are described in detail. The FORTRAN program statements and nomenclature are presented. Also, the theoretical and experimental results are compared.

INTRODUCTION

The analysis and design of thermal protection systems for entry into an atmospheric environment have resulted in a voluminous amount of literature on the general subject of ablation. (See refs. 1 and 2 for a survey of information on ablation.) The ablation materials may generally be classified into three categories: subliming, melting and vaporizing, and charring. The charring ablator normally provides the most efficient thermal-protection shield for the major portion of a manned entry vehicle. This report describes a method for predicting the thermal response of a typical charring-ablation material. The response of a charring material to a hyperthermal environment is extremely complex, and the mathematical model presented to analyze the transient behavior of the material contains simplifying assumptions and approximations necessary to afford even a numerical solution.

The equations derived in this analysis have been programmed in FORTRAN IV for an IBM 7094/40 computer system. The numerical formulation of this digital program, designated STAB II, is such that an implicit solution is obtained. The thermal response of a typical charring material as predicted by STAB II is compared with arc tunnel results.

A sample problem is presented in appendix A. Program usage instructions, including definitions of the input terminology, are presented in appendix B. Appendixes C and D are the program FORTRAN IV statements and definitions of the program terminology. A general flow chart of the program is presented in appendix E.

SYMBOLS

A	collision frequency
c_p	specific heat
E	activation energy
F	exterior view factor
F_{env}	view factor-emissivity product to cabin environment
H_d	heat of virgin material degradation
H_T	total enthalpy
H_w	wall enthalpy
H_{300}	enthalpy of air at 300° K
h	film coefficient between backup materials
h_{env}	film coefficient between last backup material and cabin environment
k	thermal conductivity
\dot{m}_c	mass loss rate of char material
\dot{m}_g	gas ablation rate
NP	number of nodes in ablation material

n	order of reaction
$Q_{in.}$	net heat rate into front surface
$\dot{q}_{c \text{ blow}}$	hot wall convective heat flux with blowing
\dot{q}_{comb}	heat flux due to combustion
\dot{q}_{cw}	cold wall convective heat flux without blowing
\dot{q}_{rad}	radiation heat flux
R	universal gas constant
S	surface recession depth
\dot{S}	surface recession rate
T	temperature of node at beginning of time step
T_{env}	cabin environment temperature
T'	temperature of node at end of time step
T_{∞}	radiation heat sink temperature
VL	thickness of ablation material
X	distance from surface to any point
ΔH_c	heat of combustion per unit weight of char
ΔX	thickness of a node
$\Delta \theta$	time step ($\theta' - \theta$)
ϵ	emissivity of material
η	transpiration cooling efficiency
θ	initial time
θ'	final time
ξ	transform for the ablation material

ρ	density
σ	Stefan-Boltzmann constant
ψ	blocking effectiveness function

Subscripts:

c	charred state
i	node number
j	material number
v	virgin state

PROGRAM DESCRIPTION

The following general requirements were established before writing a digital computer program to analyze a charring ablation system:

- (1) Stability of the equations for all applications.
- (2) Machine running time short enough to make use of the program economically feasible (a minimum of turn around time per problem).
- (3) A minimum of input per problem.
- (4) A wide variety of boundary conditions for application to both trajectory data and ground or flight test data analysis.

STAB II has been formulated in FORTRAN IV to analyze the transient thermal performance of a charring ablator heat protection system. The program considers one ablating material and up to 12 different backup materials with or without air gaps. Pure conduction or radiation and/or convection between backup materials is allowed. The ablation material may be divided into a maximum of 50 nodes, and each backup material may be subdivided into a maximum of 10 nodes. The thermal properties of the materials are in tabular form and are temperature dependent. The ablation material is also dependent upon its state, that is, fully charred, partially charred, et cetera.

The following surface boundary condition options are provided:

- (1) Cold-wall convective and radiative heat flux tables as a function of time. These components are specified separately, since mass transfer at the surface blocks part of the convective heating but, in general, has no effect on the radiant heating.

(2) Surface temperature as a function of time.

(3) Surface recession as a function of temperature or time. Surface recession as a function of temperature and pressure is also available.

Heat loss to the interior environment for the last node of the backup structure can be specified by two methods:

(1) Conduction into the node and radiation and/or convection loss to the interior environment.

(2) Conduction into the node and adiabatic wall.

The STAB II numerical formulation of the equations describing the response of the heat shield is such that an implicit solution has been obtained. It is well known that numerical solutions of partial differential equations are subject to several different types of errors. The first of these is the truncation error, due to the use of a finite subdivision. This error may be reduced by simply choosing a smaller subdivision, ΔX . The exact values are approached more and more closely as ΔX decreases. The second kind of error is the numerical, or roundoff error. The way in which this numerical error grows or decays with time determines the stability of the difference equations.

To illustrate the differences in the explicit and implicit equation form, consider a nonablating homogeneous solid. The one-dimensional Fourier conduction equation, neglecting any heat generation terms, is

$$\frac{\partial}{\partial X} \left(k \frac{\partial T}{\partial X} \right) = \rho c_p \frac{\partial T}{\partial \theta} \quad (1)$$

The finite difference form of equation (1) written in the conventional forward time step or explicit form for the i^{th} node is

Thermal resistance of half of material between nodes is $\frac{\Delta X}{2k_i}$

$$\frac{\left(\frac{T_{i-1} - T_i}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right) - \left(\frac{T_i - T_{i+1}}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} \right)}{\Delta X} = \rho c_p \frac{\Delta X (T'_i - T_i)}{\Delta \theta} \quad (2)$$

where the prime superscript denotes values at the end of the time step

$$\Delta \theta = \theta' - \theta$$

For explicit conduction solutions, the following stability criterion has been established:

$$\frac{\rho c_p}{k} \frac{(\Delta X)^2}{\Delta \theta} \geq 2$$

which places an upper limit on the time step $\Delta\theta$ for a fixed truncation error. This criterion can require a prohibitive amount of machine time.

Liebmann (ref. 3) advocated a solution of the equation which does not require this stability criterion. The finite difference equations are written in a backward time step form which affords an implicit solution.

The implicit (backward time step) difference form of equation (1) for the i^{th} node is:

$$\frac{\left(\frac{T'_{i-1} - T'_i}{\Delta X}\right)}{2k_{i-1}} + \frac{\left(\frac{T'_i - T'_{i+1}}{\Delta X}\right)}{2k_i} = \rho c_p \frac{\Delta X (T'_i - T_i)}{\Delta\theta} \quad (3)$$

Equation (3) uses the temperature differences at the end of the finite time interval instead of the beginning, as in the explicit method of equation (2). The only known temperature in equation (3) is T_i , but there are corresponding equations for each point in the system, and all are solved simultaneously to yield the temperature at each node.

Collecting all unknown temperatures on the left side of the equation and the known temperature on the right side, equation (3) becomes

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right) T'_{i-1} - \left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}\right) T'_i + \frac{\rho_i c_i \Delta X}{\Delta\theta} T'_i + \left(\frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}\right) T'_{i+1} = - \left(\frac{\rho_i c_i \Delta X}{\Delta\theta}\right) T_i \quad (4)$$

Equation (4) is of the form

$$AT'_{i-1} + BT'_i + CT'_{i+1} = D \quad (5)$$

STAB II generates such an equation for each node in the system.

Since radiation is an important mode of heat transfer in charring ablative systems, a problem is encountered in any equation containing a radiation term. The radiation heat flux, written in a backward difference form is:

$$\dot{q}_{\text{rad}} = F\epsilon\sigma (T_i^4 - T_\infty^4) \quad (6)$$

This term cannot be used in an implicit solution since the unknown temperature T'_i is to be the 4th power. The 4th power unknown can be eliminated by the following linearizations:

$$\left(T'_i\right)^4 = \left(T_i + \Delta T\right)^4 = T_i^4 \left(1 + \frac{\Delta T}{T_i}\right)^4 \quad (7)$$

where

$$\Delta T = T'_i - T_i$$

let

$$Z \equiv \frac{\Delta T}{T_i}$$

and rewrite equation (7) as

$$\left(T'_i\right)^4 = \left(T_i\right)^4 (1 + Z)^4 \quad (8)$$

If Z has an absolute value near zero, the following is true

$$(1 + Z)^4 \cong 1 + 4Z \quad (9)$$

Now substituting equation (9) into equation (8)

$$\begin{aligned} \left(T'_i\right)^4 &\cong \left(T_i\right)^4 (1 + 4Z) = \left(T_i\right)^4 \left(1 + 4 \frac{\Delta T}{T_i}\right) \\ &\cong 4T_i^3 T'_i - 3T_i^4 \end{aligned} \quad (10)$$

Equation (10) is a linearized approximation of equation (7) in which the unknown temperature is only to the first power. The assumption in equation (10) is that $\Delta T/T_i$ has an absolute value near zero. Figure 1 is a plot of the error obtained when $(1 + 4Z)$ is substituted for $(1 + Z)^4$. For most ablation problems in which the surface temperature is high and the radiation losses are significant, the value of $\Delta T/T_i$ can easily be controlled to values of less than ± 0.1 .

Therefore, equation (6) can now be written

$$\dot{q}_{\text{rad}} = F\epsilon\sigma \left(4T_i^3 T'_i - 3T_i^4 - T_\infty^4 \right) \quad (11)$$

Using the linearized approximation for the radiation terms, the resulting system of implicit difference equations constitute a tridiagonal matrix of the following form:

$$\begin{array}{rcl}
 B_1 T_1 + C_1 T_2 & & = D_1 \\
 A_2 T_1 + B_2 T_2 + C_2 T_3 & & = D_2 \\
 A_3 T_2 + B_3 T_3 + C_3 T_4 & & = D_3 \\
 \vdots & \vdots & \vdots \\
 A_N T_{N-1} + B_N T_N & = & D_N
 \end{array}$$

Gauss' elimination method, discussed in reference 4, is applied to solve the system of equations. This method affords a fast and accurate solution for matrices containing a dominant diagonal. The solution of this matrix gives the temperature of each node in the system for the next future time step. The entire process is repeated for each time step throughout the run, giving a time history of the temperature at each node.

Using this method of solution, residual errors in the temperature computations at the beginning of the time step are distributed throughout the entire system of nodal equations and tend to cancel out rapidly. The principal advantage in using the implicit method is a set of equations that are mathematically stable in time and distance. Therefore, the magnitude of the time step is not limited by a convergence criterion. However, care must be taken in selecting the magnitude of the time step in order to minimize truncation errors when the second derivative of temperature with respect to time is large. A similar approach is used to minimize truncation errors in distance by choosing small node dimensions in locations where large second derivatives of temperature with respect to distance are expected.

In the case of a char-forming ablative heat shield where approximately 80 percent of the heat is reradiated, instability can arise in taking large time steps. The temperature of the surface node can start oscillating on successive time steps when a balance between the radiation source and the heat sink has been achieved. Therefore, in ablation problems in which the surface node loses a large percentage of heat by radiation, oscillations of the node can be damped out by taking small time steps during conditions of high heat flux and near radiation equilibrium temperatures.

ANALYSIS

Figure 2 is a schematic of the thermal protection system to be analyzed. A receding surface has been assumed with the formation of a residual char layer and reaction zone. The thermal protection system is composed of one charring material and a maximum of 12 different backup materials with or without air gaps.

The analysis is such that the entire system may be composed of noncharring materials. The thermal properties of all materials are temperature dependent; also, the charring material properties are state dependent (fully or partially charred).

The response of charring ablation heat shields to a hyperthermal environment is extremely complex, and simplifying assumptions and approximations are necessary to afford a numerical solution. The following assumptions and approximations are utilized in the equations developed in this report:

(1) The material decomposes from the virgin state to a porous char layer in the reaction zone.

(2) The reaction zone can be defined by an upper and lower temperature limit.

(3) The gas generated within the reaction zone is assumed to pass out of the structure with no pressure loss. No gas accumulation within a node is allowed.

(4) Local thermal equilibrium is maintained between the gas and porous char matrix.

(5) The gas undergoes no further chemical reaction within the residual material after having been formed.

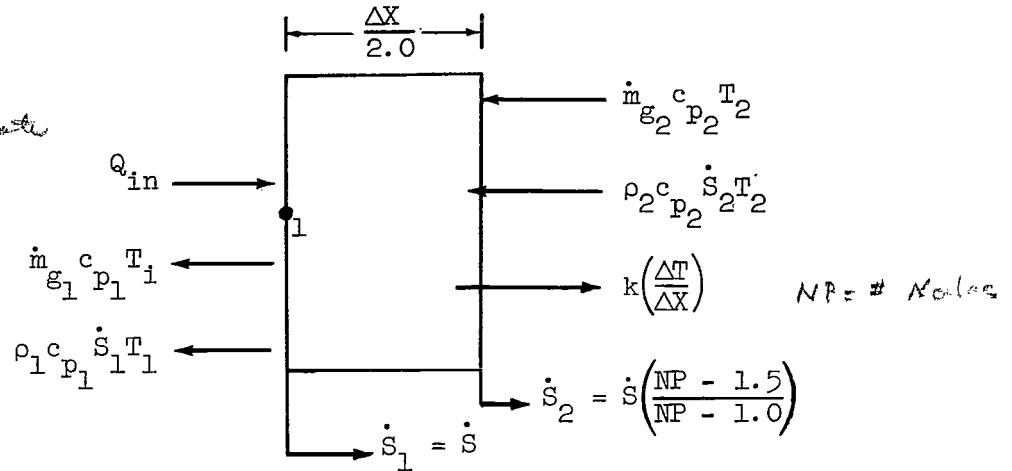
Derivation of Equations

The equations are derived for a moving boundary coordinate system, where the front face is the moving surface (ref. 5). With this system, the ablating material is divided into a fixed number of nodes of thickness ΔX which depends on the instantaneous location of the front face. The surface recession is handled in a continuous manner, eliminating the need of throwing away or lumping off of nodes.

The physical model for the front surface, including all heating terms, is shown as follows:

$\dot{m}_g = g_0$ - ablation rate

\dot{S} - surface recession rate



The energy equation at the front char surface is

$$\begin{aligned} \frac{d}{d\theta} \left(\frac{1}{2} \Delta X \rho_1 c_{p1} T_1 \right) &= \frac{1}{2} \Delta X \rho_1 c_{p1} \frac{dT_1}{d\theta} + \frac{1}{2} \rho_1 c_{p1} T_1 \frac{d(\Delta X)}{d\theta} \\ &= Q_{in} + \dot{m}_{g2} c_{p2} T_2' + \rho_2 \dot{S}_2 c_{p2} T_2' - \dot{m}_{g1} c_{p1} T_1' \\ &\quad - \rho_1 c_{p1} \dot{S}_1 T_1' - k_{1-2} \left(\frac{\Delta T}{\Delta X} \right) \end{aligned} \quad (12)$$

where

$$Q_{in} = \dot{q}_{c, \text{blow}} + \dot{q}_{\text{rad}} + \dot{q}_{\text{comb}} - F\epsilon\sigma (T_1^4 - T_\infty^4)$$

and

$$\frac{d(\Delta X)}{d\theta} = \frac{d}{d\theta} \left(\frac{VL - S}{NP - 1} \right) = - \frac{\dot{S}}{NP - 1}$$

where \dot{S} is the linear surface recession rate and NP is the total number of nodes in the ablation material of thickness $= VL$.

Rewriting equation (12) in implicit finite difference form

$$\begin{aligned}
 Q_{in} + \dot{m}_{g_2} c_{p_2} T'_2 - \dot{m}_{g_1} c_{p_1} T'_1 - \dot{S} \rho_1 c_{p_1} T'_1 - \frac{\left(\frac{T'_1}{2k_1} - \frac{T'_2}{2k_2} \right)}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} \\
 + \rho_2 c_{p_2} \dot{S} \left(\frac{NP - 1.5}{NP - 1.0} \right) T'_2 = \rho_1 c_{p_1} \frac{\Delta X}{2} \left(\frac{T'_1 - T_1}{\Delta \theta} \right) \\
 - \frac{1}{2} \rho_1 c_{p_1} T'_1 \left(\frac{\dot{S}}{NP - 1} \right)
 \end{aligned} \tag{12a}$$

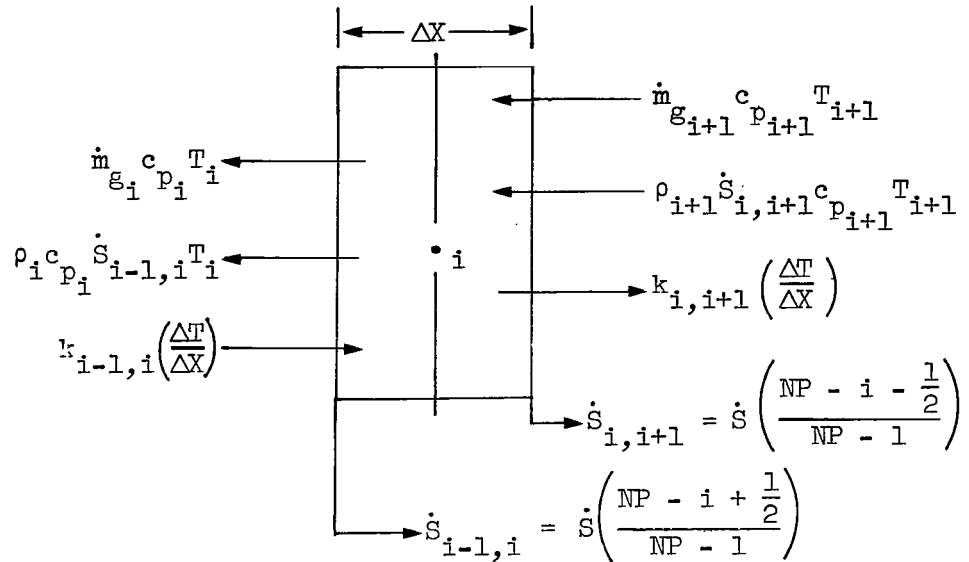
Then, rearranging and collecting terms yield

$$\begin{aligned}
 - \left[\dot{m}_{g_1} c_{p_1} + \dot{S} \rho_1 c_{p_1} + \rho_1 c_{p_1} \frac{\Delta X}{2\Delta \theta} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} - \frac{1}{2} \rho_1 c_{p_1} \left(\frac{\dot{S}}{NP - 1} \right) \right] T'_1 \\
 + \left[\dot{m}_{g_2} c_{p_2} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} + \rho_2 c_{p_2} \dot{S} \left(\frac{NP - 1.5}{NP - 1.0} \right) \right] T'_2 \\
 = -\rho_1 c_{p_1} \frac{\Delta X}{2\Delta \theta} T_1 - Q_{in}.
 \end{aligned}$$

FRONT
SURFACE

(12b)

The physical model for interior points in the mature char zone, including all heating terms, is shown in the following sketch:



The energy equation for interior points in the char matrix is

$$\begin{aligned} \frac{d}{d\theta} \left(\Delta X_i \rho_i c_{p_i} T_i \right) &= \Delta X_i \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i' \left(\frac{\dot{S}}{NP - 1} \right) \\ &= \dot{m}_{g_{i+1}} c_{p_{i+1}} T_{i+1}' + k_{i-1,i} \left(\frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1} \right) T_{i+1}' \\ &\quad - k_{i,i+1} \left(\frac{\Delta T}{\Delta X} \right) - \dot{m}_{g_i} c_{p_i} T_i' - \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1} \right) T_i' \end{aligned} \quad (13)$$

Putting equation (13) in an implicit finite difference form yields

$$\begin{aligned}
 \left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right) T'_{i-1} - \left[\dot{m}_{g_i} c_{p_i} + \rho_i c_{p_i} \dot{s} \left(\frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right. \\
 \left. + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i} \left(\frac{\dot{s}}{NP - 1} \right) \right] T'_i \\
 + \left[\dot{m}_{g_{i+1}} c_{p_{i+1}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{s} \left(\frac{NP - i - \frac{1}{2}}{NP - 1} \right) \right] T'_{i+1} \\
 = -\rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} T'_i
 \end{aligned}$$

CHAR
ZONE

(13a)

In the mature char zone, no internal gaseous ablation products are assumed to form. The reaction zone is the source for the formation of the internal gaseous products. Therefore, in equations (12) and (13), $\dot{m}_{g_i} = \dot{m}_{g_{i+1}}$

The physical model for nodes in the reaction zone is identical to schematic shown for the interior nodes in the char except for considering the energy absorbed in formation of the gaseous ablation products. The heat balance equation for a node in the reaction zone is

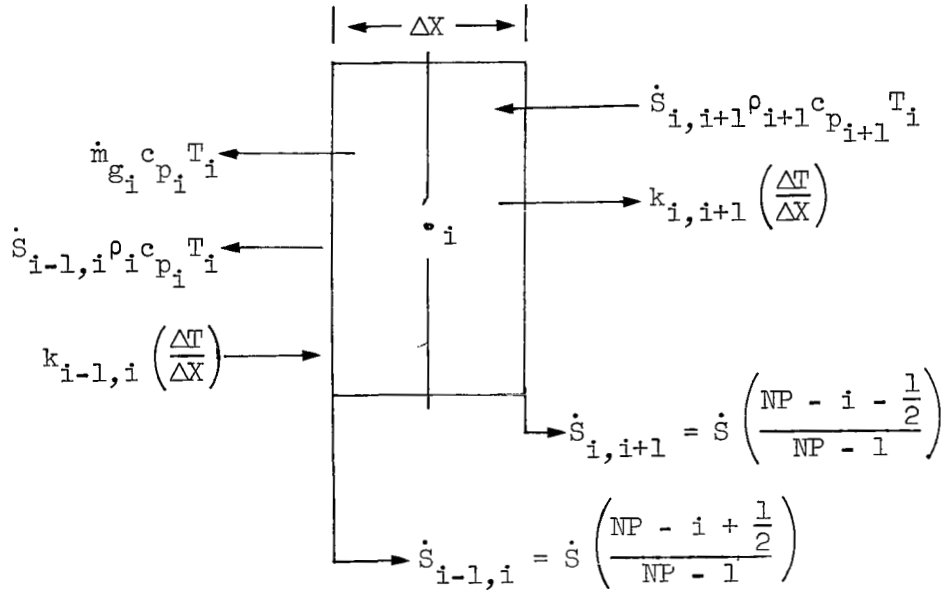
$$\begin{aligned}
 \frac{d}{d\theta} (\Delta X \rho_i c_{p_i} T'_i) &= \Delta X \rho_i c_{p_i} \frac{dT'_i}{d\theta} - \rho_i c_{p_i} T'_i \left(\frac{\dot{s}}{NP - 1} \right) - (\dot{m}_{g_i} - \dot{m}_{g_{i+1}}) H_d \\
 &= \dot{m}_{g_{i+1}} c_{p_{i+1}} T'_{i+1} + k_{i-1,i} \left(\frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{s} \left(\frac{NP - i - \frac{1}{2}}{NP - 1} \right) T'_{i+1} \\
 &\quad - k_{i,i+1} \left(\frac{\Delta T}{\Delta X} \right) - \dot{m}_{g_i} c_{p_i} T'_i - \rho_i c_{p_i} \dot{s} \left(\frac{NP - i + \frac{1}{2}}{NP - 1} \right) T'_i
 \end{aligned} \tag{14}$$

Rearranging,

$$\begin{aligned}
 & \left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right) T'_{i-1} - \left[\dot{m}_{g_i} c_{p_i} + \rho_i c_{p_i} \dot{s} \left(\frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right. \\
 & \quad + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i} \left(\frac{\dot{s}}{NP - 1} \right) \left. \right] T'_i + \left[\dot{m}_{g_{i+1}} c_{p_{i+1}} \right. \\
 & \quad \left. + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{s} \left(\frac{NP - i - \frac{1}{2}}{NP - 1} \right) \right] T'_{i+1} \\
 & = -\rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} T_i - \left(\dot{m}_{g_i} - \dot{m}_{g_{i+1}} \right) H_d \quad (14a)
 \end{aligned}$$

REACTION
ZONE

The physical model for the interface between the reaction zone and virgin material is illustrated as follows:



The heat balance equation for this node is

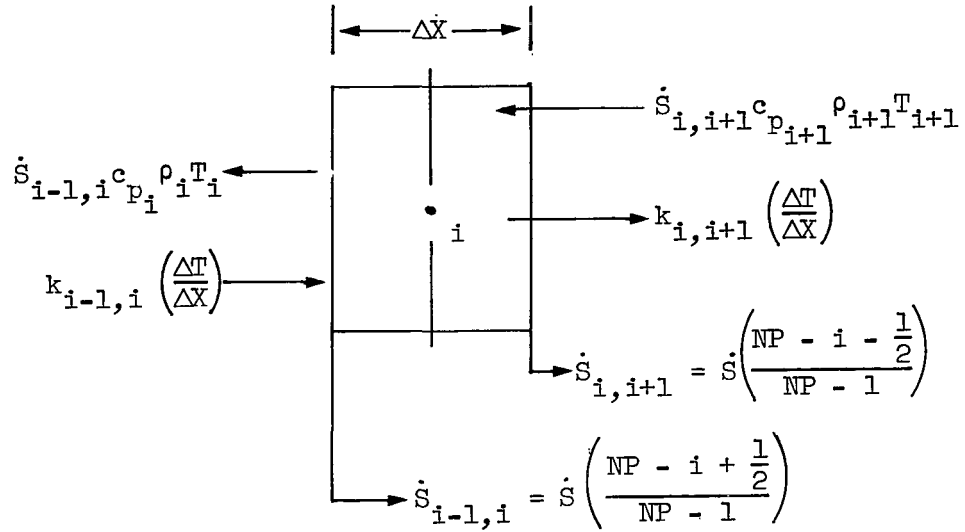
$$\begin{aligned}
\frac{d}{d\theta} \left(\Delta X \rho_i c_{p_i} T_i \right) &= \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i' \left(\frac{\dot{S}}{NP - 1} \right) - \dot{m}_{g_i} H_d \\
&= k_{i-1,i} \left(\frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1} \right) T_{i+1}' \\
&\quad - k_{i,i+1} \left(\frac{\Delta T}{\Delta X} \right) - \dot{m}_{g_i} c_{p_i} T_i' - \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1} \right) T_i'
\end{aligned} \tag{15}$$

Rearranging yields

$$\begin{aligned}
\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right) T_{i-1}' &- \left[\dot{m}_{g_i} c_{p_i} + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} \right. \\
&+ \left. \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i} \left(\frac{\dot{S}}{NP - 1} \right) \right] T_i' \\
&+ \left[\frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1} \right) \right] T_{i+1}' \\
&= -\rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} T_i' - \dot{m}_{g_i} H_d
\end{aligned} \tag{15a}$$

INTERFACE

The physical model for an interior node in the virgin material is



The heat balance for this nonablating node is

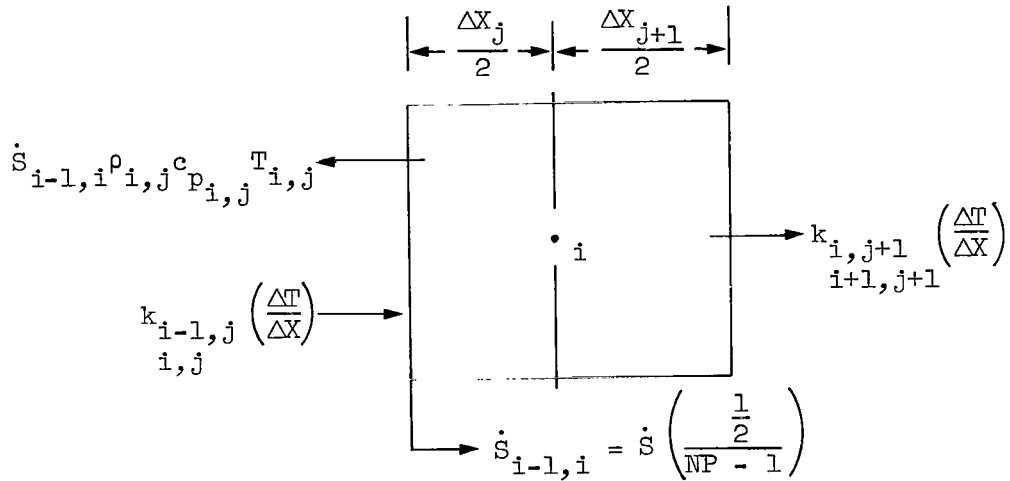
$$\begin{aligned}
 \frac{d}{d\theta} \left(\Delta X \rho_i c_{p_i} T'_i \right) &= \Delta X \rho_i c_{p_i} \frac{dT'_i}{d\theta} - \rho_i c_{p_i} T'_i \left(\frac{\dot{S}}{NP - 1} \right) \\
 &= k_{i-1,i} \left(\frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1} \right) T'_{i+1} - k_{i,i+1} \left(\frac{\Delta T}{\Delta X} \right) \\
 &\quad - \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1} \right) T'_i \quad (16)
 \end{aligned}$$

Rearranging,

$$\begin{aligned}
 & \left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right) T'_{i-1} - \left[\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} \right. \\
 & \left. + \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i} \left(\frac{\dot{S}}{NP - 1} \right) \right] T'_i \\
 & + \left[\frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1} \right) \right] T'_{i+1} = -\rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} T_i \quad (16a)
 \end{aligned}$$

YIELD

The physical model for the last node in the ablation material and first node in the backup structure is



For this interface, $T'_{i,j} = T'_{i,j+1}$.

The heat balance equation for this node is

$$\begin{aligned}
 & \frac{d}{d\theta} \left[\left(\frac{\Delta X_j}{2} \rho_{i,j} c_{p_{i,j}} + \frac{\Delta X_{j+1}}{2} c_{p_{i,j+1}} \rho_{i,j+1} \right) T_i \right] \\
 &= \left(\frac{\Delta X_j \rho_{i,j} c_{p_{i,j}} + \Delta X_{j+1} c_{p_{i,j+1}} \rho_{i,j+1}}{2} \right) \frac{dT_i}{d\theta} - \frac{1}{2} \left(\frac{\dot{S}}{NP - 1} \right) c_{p_{i,j}} \rho_{i,j} T'_i \\
 &= k_{i-1,j} \left(\frac{\Delta T}{\Delta X} \right)_{i,j} - c_{p_{i,j}} \rho_{i,j} \dot{S} \left(\frac{1}{NP - 1} \right) T'_i - k_{i,j+1} \left(\frac{\Delta T}{\Delta X} \right)_{i+1,j+1} \quad (17)
 \end{aligned}$$

Rearranging yields

$$\begin{aligned}
 & \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1} - \left[\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right. \\
 & \left. + \left(\frac{\Delta X_j \rho_{i,j} c_{p_{i,j}} + \Delta X_{j+1} c_{p_{i,j+1}} \rho_{i,j+1}}{2\Delta\theta} \right) T'_i + \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right) T'_{i+1} \right. \\
 & \left. = - \left(\frac{\Delta X_j c_{p_{i,j}} \rho_{i,j} + \Delta X_{j+1} c_{p_{i,j+1}} \rho_{i,j+1}}{2\Delta\theta} \right) T_i \right. \quad (17a)
 \end{aligned}$$

The backup structure may contain up to a maximum of 12 different materials with or without air gaps between materials. Therefore, conduction or radiation and/or convection between materials is allowed. The heat balance equations for the various modes of heat transfer in the backup structure are presented in the following equations:

(1) Interior node material:

$$\frac{\left(\frac{T'_{i-1,j} - T'_{i,j}}{\Delta X_j} \right)}{\frac{1}{2k_{i-1,j}} + \frac{1}{2k_{i,j}}} - \frac{\left(\frac{T'_{i,j} - T'_{i+1,j}}{\Delta X_j} \right)}{\frac{1}{2k_{i,j}} + \frac{1}{2k_{i+1,j}}} = \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} (T'_{i,j} - T_{i,j}) \quad (18)$$

Rearranging, equation (18) becomes

$$\begin{aligned} & \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_j}{2k_{i,j}} + \frac{\Delta X_j}{2k_{i+1,j}}} \right) \\ & + \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} T'_{i,j} + \left(\frac{1}{\frac{\Delta X_j}{2k_{i,j}} + \frac{\Delta X_j}{2k_{i+1,j}}} \right) T'_{i+1,j} \\ & = -\rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} T_{i,j} \quad (18a) \end{aligned}$$

(2) First and last nodes of two interior materials with no gap:

$$\begin{aligned} & \frac{\left(\frac{T'_{i-1,j} - T'_{i,j}}{\Delta X_j} \right)}{\frac{1}{2k_{i-1,j}} + \frac{1}{2k_{i,j}}} - \frac{\left(\frac{T'_{i,j+1} - T'_{i+1,j+1}}{\Delta X_{j+1}} \right)}{\frac{1}{2k_{i,j+1}} + \frac{1}{2k_{i+1,j+1}}} \\ & = \left(\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + \rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2 \Delta \theta} \right) (T'_{i,j} - T_{i,j}) \quad (19) \end{aligned}$$

For this case, $T'_{i,j} = T'_{i,j+1}$

Rearranging, equation (19) becomes

$$\begin{aligned}
& \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left[\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right. \\
& \quad \left. + \left(\frac{\rho_{i,j}^c p_{i,j} \Delta X_j + \rho_{i,j+1}^c p_{i,j+1} \Delta X_{j+1}}{2 \Delta \theta} \right) \right] T'_{i,j} \\
& \quad + \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right) T'_{i+1,j+1} \\
& = - \left(\frac{\rho_{i,j}^c p_{i,j} \Delta X_j + \rho_{i,j+1}^c p_{i,j+1} \Delta X_{j+1}}{2 \Delta \theta} \right) T_{i,j} \quad (19a)
\end{aligned}$$

(3) First node of interior material with an air gap between materials:

$$\begin{aligned}
& h_j (T'_{i-1,j} - T'_{i,j+1}) + \left(\frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) (T'^4_{i-1,j} - T'^4_{i,j+1}) \\
& - \left(\frac{T'_{i,j+1} - T'_{i+1,j+1}}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right) = \frac{\rho_{i,j+1}^c p_{i,j+1} \Delta X_{j+1}}{2 \Delta \theta} (T'_{i,j+1} - T_{i,j+1}) \quad (20)
\end{aligned}$$

Equation (20) may be linearized by using the approximation

$$T'^4 \cong 4T^3 T' - 3T^4$$

as discussed in the Program Description section.

Therefore, rearranging and linearizing, equation (20) becomes

$$\begin{aligned}
& \left[h_j + \left(\frac{4\sigma T_{i-1,j}^3}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \right] T'_{i-1,j} - \left[h_j + \left(\frac{4\sigma T_{i,j+1}^3}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \right. \\
& \quad \left. + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} + \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2 \Delta \theta} \right] T'_{i,j+1} \\
& \quad + \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right) T'_{i+1,j+1} = - \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2 \Delta \theta} T_{i,j+1} \\
& \quad - \left(\frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \left(T_{i,j+1}^4 - T_{i-1,j}^4 \right) \quad (20a)
\end{aligned}$$

(4) Last node of an interior material with an air gap between materials:

$$\begin{aligned}
& \frac{\left(\frac{T'_{i-1,j} - T'_{i,j}}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right)}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} - h_j (T'_{i,j} - T'_{i,j+1}) \\
& - \left(\frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \left(T_{i,j}^4 - T_{i,j+1}^4 \right) = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2 \Delta \theta} \left(T'_{i,j} - T_{i,j} \right) \quad (21)
\end{aligned}$$

Rearranging and linearizing, equation (21) becomes

$$\begin{aligned}
& \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left[h_j + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \left(\frac{4\sigma T_{i,j}^3}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \right. \\
& \quad \left. + \frac{\rho_{i,j}^c p_{i,j} \Delta X_j}{2 \Delta \theta} \right] T'_{i,j} + \left[h_j + \left(\frac{4\sigma T_{i,j+1}^3}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \right] T'_{i,j+1} \\
& = - \frac{\rho_{i,j}^c p_{i,j} \Delta X_j}{2 \Delta \theta} T_{i,j} + \left(\frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) (T_{i,j+1}^4 - T_{i,j}^4)
\end{aligned} \tag{21a}$$

(5) Final node in backup structure:

(a) Adiabatic surface -

$$\frac{T'_{i-1,j} - T'_{i,j}}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} = \frac{\rho_{i,j}^c p_{i,j} \Delta X_j}{2 \Delta \theta} (T'_{i,j} - T_{i,j}) \tag{22}$$

Rearranging, equation (22) becomes

$$\begin{aligned}
& \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right. \\
& \quad \left. + \frac{\rho_{i,j}^c p_{i,j} \Delta X_j}{2 \Delta \theta} \right) T'_{i,j} = - \frac{\rho_{i,j}^c p_{i,j} \Delta X_j}{2 \Delta \theta} T_{i,j}
\end{aligned} \tag{22a}$$

(b) Radiation and/or convection loss to cabin environment -

$$\left(\frac{\frac{T'_{i-1,j} - T'_{i,j}}{\Delta X_j}}{\frac{1}{2k_{i-1,j}} + \frac{1}{2k_{i,j}}} \right) - h_{\text{env}} (T'_{i,j} - T_{\text{env}}) - F_{\text{env}} \sigma (T_{i,j}^4 - T_{\text{env}}^4) = \frac{\rho_{i,j}^c p_{i,j} \Delta X_j}{2 \Delta \theta} (T'_{i,j} - T_{i,j}) \quad (23)$$

Rearranging, equation (23) becomes

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left(h_{\text{env}} + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + F_{\text{env}} \sigma T_{i,j}^3 + \frac{\rho_{i,j}^c p_{i,j} \Delta X_j}{2 \Delta \theta} \right) T'_{i,j} = - \frac{\rho_{i,j}^c p_{i,j} \Delta X_j}{2 \Delta \theta} T_{i,j} - h_{\text{env}} T_{\text{env}} - F_{\text{env}} \sigma (3T_{i,j}^4 + T_{\text{env}}^4) \quad (23a)$$

Discussion of Assumptions

A brief discussion of several assumptions and approximations made in deriving the heat balance equations is now presented.

As shown in the Derivation of Equations section, transient heat conduction, thermal degradation, and the flow of the gaseous products from the reaction zone are the internal thermal transport phenomena of interest. Several methods are available in the treatment of the thermal decomposition process, and they differ primarily in whether the chemical decomposition occurs in a single plane at a fixed temperature or whether a spatially continuous decomposition in depth is assumed. This analysis assumes that the decomposition from the virgin to the char state occurs in a reaction zone that is defined by known temperature limits. These temperature limits are determined from thermogravimetric test data for the particular material being investigated. Figure 3 is a thermogravimetric curve for typical charring ablation material. From this curve, the rate of pyrolysis \dot{m}_g is calculated by knowing the

temperature change of a particular node with time, that is,

$$\dot{\rho}_i = \frac{\rho_i' - \rho_i}{\Delta\theta} \quad (24)$$

and

$$\dot{m}_{g_i} = \sum_i^{NP} \dot{\rho}_i \Delta X_i \quad (25)$$

This method of computing the gas-generation rates and local instantaneous density may be subject to error since the thermogravimetric curve of a material is influenced by temperature rise rate (deg/sec), and the reaction zone may shift up and down the temperature scale. This error can be eliminated by the use of an Arrhenius expression of the form

$$\frac{d\rho}{d\theta} = -A(\rho - \rho_c)^n e^{-\frac{E}{RT}} \quad (26)$$

The method now being used in STAB II (equation (25)) to calculate the pyrolysis rate is being investigated to determine its validity. The final formulation of the pyrolysis rate law must rest heavily on the experimental rate data for the material under investigation. The use of simple expressions such as equations (24) and (25) may be entirely adequate, depending upon activation energy for the decomposition process and order of reaction.

The aerodynamic heating input in the analysis consists of convective and radiative components treated separately. This distinction is necessary since the convective heating can be significantly reduced as a result of the injection of the ablation gases into the boundary layer, with generally no effect on radiant heating. Reduction in the convective heating rate can be approximated by the following expression (ref. 6):

$$\dot{q}_{\text{block}} \equiv \eta \dot{m}_g (H_T - H_w) \quad (27)$$

Therefore,

$$\dot{q}_{c, \text{blow}} = \dot{q}_{cw} \left(\frac{H_T - H_w}{H_T - H_{300}} \right) - \dot{q}_{\text{block}} \quad (28)$$

However, equation (28) is unsatisfactory for high blowing rates, since \dot{q}_{block} can become greater than \dot{q}_{cw} . An experimental curve of blocking effectiveness $\psi = \frac{\dot{q}_{\text{c, blow}}}{\dot{q}_{\text{cw}}}$ as a function of the mass transfer parameter $\frac{\dot{m}_c H_T}{\dot{q}_{\text{cw}}}$ can be employed to determine the heating reduction at high blowing rates. Both methods have been employed in the STAB II analysis. Equation (28) is presently in use. However, no satisfactory method for accurately predicting the convective heat blockage has been determined.

Another source of heating is the combustion of the ablation products in the boundary layer. Reference 7 presents an analysis of the oxidation of a carbon surface and the resulting combustive heating. The heating due to combustion as derived in reference 7 is

$$\dot{q}_{\text{comb}} = \dot{m}_c \Delta H_c \quad (29)$$

where ΔH_c is the heat of combustion per unit weight of char.

The thermal properties of the ablation material are both temperature and state dependent (fully or partially charred). Figure 4 is an illustration of the variation of these properties with temperature and state. The thermal properties are assumed to vary as follows:

$$(1) \text{ Char zone } (T_i \geq T_{\text{char}})$$

$$k_c = f(\text{temp})$$

$$c_{p_c} = f(\text{temp})$$

$$\rho_c = \text{constant}$$

$$(2) \text{ Reaction zone } (T_{\text{abl}} \leq T_i < T_{\text{char}})$$

$$\rho = f(\text{temp}) = \rho_v + (\rho_v - \rho_c) \left(\frac{T_i - T_{\text{abl}}}{T_{\text{abl}} - T_{\text{char}}} \right)$$

$$k = f(\rho) = k_c + (k_v - k_c) \left(\frac{\rho_i - \rho_c}{\rho_v - \rho_c} \right)$$

$$c_p = f(\rho) = c_{p_c} + (c_{p_v} - c_{p_c}) \left(\frac{\rho_i - \rho_c}{\rho_v - \rho_c} \right)$$

(3) Virgin zone $\left(T_i < T_{abl}\right)$

$$\rho_v = \text{constant}$$

$$k_v = f(\text{temp})$$

$$c_{p_v} = f(\text{temp})$$

The calculation of char removal, due to chemical, thermal, or mechanical mechanism or a combination of these mechanisms, has been examined by a multitude of investigators and numerous correlations exist, depending on the specific material involved.

To provide a maximum degree of flexibility for analyzing both ground and flight test data and synthesizing trajectories, the following provisions for char removal (surface movement) are provided:

- (1) Removal of char as a function of surface temperature.
- (2) Removal of char at a rate which is a function of time.

As the char is removed, the surface moves with respect to a coordinate fixed in the material. The distance between the initial surface location and the char surface is

$$S = \int_0^{\theta} \dot{S} d\theta$$

ANALYSIS VERIFICATION

As discussed in the previous sections, approximations and assumptions were made in the analytical model to afford a quick and accurate solution in predicting the thermal response of a charring heat shield. These simplifying assumptions and approximations are expected to introduce only minor errors; however, the validity of the analyses and resultant accuracy can be judged only by a comparison with exact theoretical solutions and experimental data. Three examples have been selected, and a comparison of the STAB II results with the theoretical and test data is discussed in the following paragraphs.

An elementary transient heating example was chosen to demonstrate the accuracy and numerical stability of the STAB II program. A steel slab 6 inches thick was selected and assumed to be at uniform initial temperature of 460° R (0° F). The thermal properties were considered constant. The

front surface was subjected to a heating rate of 72 Btu/ft²-sec, and an adiabatic back surface was assumed. Figure 5 shows a comparison of the STAB II calculated in-depth temperatures as a function of time with the exact solution taken from reference 8.

To demonstrate the STAB II solution with a moving boundary, a slab with constant properties, uniform initial temperature, front surface moving with a constant velocity, and constant surface temperature was chosen. The exact solution for a semi-infinite slab with these boundary and initial conditions is presented in reference 9. Figure 6 presents a comparison of the STAB II temperature response with the exact solutions. As can be seen from this figure, the two solutions are not in agreement for approximately the first 50 to 60 seconds of the transient. This disagreement is the result of the quasi-steady state assumption made in the exact solution analysis.

$$\left[\left(\frac{\partial T}{\partial \theta} \right)_{\xi=0} = 0; k \left(\frac{\partial T}{\partial X} \right)_{X=0} = \dot{s} \rho c_p \Delta T \right]$$

A calculation was made to estimate the induction time (time at which $\frac{\partial T}{\partial \theta} = 0$ is a good assumption) and found to be approximately 60 seconds, which is in agreement with the STAB II results.

Finally, to verify the fully charring ablation model, an example of a typical charring material was chosen. (See the sample problem in appendix A.) The charring ablation material is initially 1.6 inches thick with an adiabatic back surface and a constant heat flux of 95 Btu/ft²-sec applied to the front surface. The surface is assumed to recede at a constant velocity of 3.05×10^{-3} in./sec. Figure 7 presents a comparison of the in-depth temperatures with actual test results obtained in an arc tunnel. The results are in good agreement, with the largest deviations between calculated and measured values occurring for the thermocouple located at a depth of 1.0 inch. The disagreement could be attributed to several possible errors: thermal property values, incorrect location of thermocouples, et cetera. The effect of varying the thermal properties (thermal conductivity, specific heat, et cetera) is presently being investigated.

Tables I and II present the input and output data used for this example. Figures 8, 9, and 10 are the resulting plot routine output.

The comparisons between the computer results and the exact solutions and test results are considered satisfactory.

CONCLUDING REMARKS

An analysis and a computer program for predicting the transient thermal response of a charring ablation thermal protection system has been described. The numerical formulation of the equations is such that an implicit solution is obtained. This method of solution affords both a rapid and accurate solution for both ablating and nonablating type problems.

Provision is made in the program for a number of surface boundary conditions. These provisions allow efficient use of the program for analyzing both ground and flight test data and trajectory synthesis.

The computer program has been checked out with both exact solutions and actual ablation test data. The numerical results are in good agreement with the exact solutions and test data. However, the analysis depends upon using good property values, and some effort must be expended in obtaining the best possible thermal properties.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, November 1, 1965

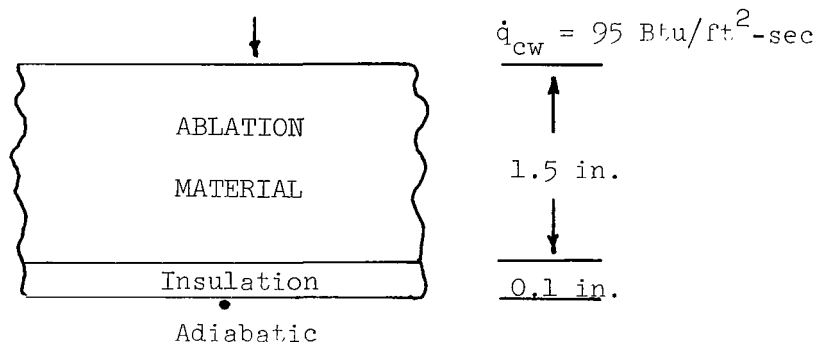
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APPENDIX A

SAMPLE PROBLEM

The following sample problem is shown to indicate the form of the data input and the program output. A typical charring material subjected to a constant heating rate as experienced in an arc tunnel is presented. The following is a sketch of the model:



The various material properties and dimensions are shown in the program output of Table II. The insulation is assumed to be ablation material for this problem. The problem coding sheet and subsequent data card listing are shown in Table I. The initial temperature of the structure was assumed uniform and equal to 530° R (70° F). Figures 8, 9, and 10 are the output data obtained from the plot routines.

APPENDIX B

PROGRAM USAGE INSTRUCTIONS

IBM 7094/40 program F021, standard ablation program, designated STAB II, is designed to evaluate the transient thermal performance of a charring ablation heat protection system. The program considers one ablating material and up to 12 different materials in the supporting backup structure. A maximum of 50 nodes may be considered in the ablation material, and a maximum of 10 nodes per material is allowed for each backup structure material. Air gaps can be considered between successive materials in the backup, thus allowing for both radiative and/or convective heat transfer between materials. The heat loss to the cabin environment from the backup structure can be accomplished by both radiation and/or convection, or an adiabatic backface surface may be prescribed.

Unless otherwise specified, the input problem data are in "floating point" form (E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. It is suggested that each floating point number have a sign, a two-digit exponent, and a decimal point. For example, the number 145.23 can be written as +1.4523 +02, +145.23 +00, or +.14523 +03.

Input Nomenclature

The nomenclature used in the problem data input is as follows:

NCASE	number of problems to be run successively
HEAD	any 72 alphabetical and/or numerical characters
TITLE	control card for reading in new input for successive problems
	1. blank card - new data will be read in
	2. Six asterisks in columns 1 to 6. Skip to next read statement
TLIM	time limit of problem, sec
TINT	starting time of problem, sec
NPTT	number of points in time-step table (the minimum value of NPTT is 2)
NPL OT	output plot control
=1	plot routine will be used
=0	plot routine will be ignored

TTABLE	time in time-step table, sec
DELTT	time step to be used for each calculation - starting at time TTABLE, sec
IPRC	variable print frequency in TTABLE table; that is, if DELTT = 1.0 and IPRC = 10, the output will be printed at 10-second intervals
FC Ø NV	factor to correct convective heating rate for various body locations
FRAD	factor to correct radiative heating for various body locations
TABL	temperature at which ablation starts, °R
TCHAR	temperature at which ablation stops, °R
TREC	surface temperature, °R, <u>or</u> time at which char removal is to start, sec
RH Ø V	density of virgin ablation material, lb/ft ³
RH Ø C	density of mature char material, lb/ft ³
FBL Ø W	blowing efficiency of ablation gases in reducing convective heating
EMV	emissivity of virgin ablation material
EMC	emissivity of charred ablation material
H300	enthalpy of air at 300° K, 129.06 Btu/lbm
VL	initial thickness of virgin ablation material, in.
HV	heat of degradation of virgin material, Btu/lbm
VPT	test to determine if the reaction zone and char zone thermal properties are irreversible with temperature
=0	properties are irreversible and equal to the value at the maximum individual node temperature (this is the recommended value for VPT)
=1	properties are reversible
FV	view factor for external environment
TV	sink temperature of external environment, °R

CHARK	thermal conductivity of material at TCHAR, Btu/ft-hr- [°] R
CHARC	specific heat of material at TCHAR, Btu/lbm- [°] R
ABLK	thermal conductivity of material at TABL, Btu/ft-hr- [°] R
ABLC	specific heat of material at TABL, Btu/lbm- [°] R
NP	number of node points in ablation material
NKC	number of points in char thermal conductivity - temperature table
NCPC	number of points in char specific heat - temperature table
NKV	number of points in virgin thermal conductivity - temperature table
NCPV	number of points in virgin specific heat - temperature table
NREC	number of points in surface recession - temperature <u>or</u> time table
TKC	temperature values in char thermal conductivity - temperature table, [°] R
XKC	thermal conductivity values in char thermal conductivity - temperature table, Btu/ft-hr- [°] R
TCPC	temperature values in char specific heat - temperature table, [°] R
CPC	specific heat values in char specific heat - temperature table, Btu/lbm- [°] R
TKV	temperature values in virgin thermal conductivity - temperature table, [°] R
XKV	thermal conductivity values in virgin thermal conductivity - temperature table, Btu/ft-hr- [°] R
TCPV	temperature values in virgin specific heat - temperature table, [°] R
CPV	specific heat values in virgin specific heat temperature table, Btu/lbm- [°] R
TS	temperature, [°] R, or time, sec, values in the surface recession table

SR	surface recession values in the surface recession - temperature or time table, in./sec
NTRAPT	number of time points in the trajectory input table
TIME	the array of (NTRAPT) trajectory time values, sec
QCØN	the corresponding array of cold wall convective heating rates, Btu/ft ² -sec
QRAD	the corresponding array of radiative heating rates, Btu/ft ² -sec
VEL	the corresponding array of flight velocity, ft/sec
NMB	number of materials in backup structure
NPBS	total number of node points in backup structure
BL	total thickness of backup structure, in.
XNPM	number of nodes in <u>each individual</u> material in backup structure
NKPB	number of points in <u>each individual</u> backup structure material thermal conductivity - temperature table
NCPB	number of points in <u>each individual</u> backup structure material specific heat - temperature table
XIDNT	any 72 alphanumeric characters used to describe <u>each</u> <u>individual</u> material in the backup structure
TXK	temperature values in backup material thermal conductivity - temperature table, °R
XK	thermal conductivity values in backup material thermal conductivity - temperature table, Btu/ft-hr-°R
TCP	temperature values in backup material specific heat - temperature tables, °R
CPX	specific heat values in backup material specific heat - temperature tables, Btu/lbm-°R
RHØBX	density of individual materials in backup, lb/ft ³
XBM	thickness of individual materials in backup, in.
EMFB	emissivity of front surface of each material in backup

EMBB	emissivity of back surface of each material in backup
H	film coefficient between adjacent materials in backup, Btu/ft ² -hr-°R
GAPX	width of gap between adjacent materials in backup, in.
FTEST, BTEST	tests to determine the mode of heat transfer between materials for the front and backface of each material respectively
=0	conduction only between materials
=+1	convective heat transfer only
=-1	radiation only or radiation and convection heat transfer
TENV	temperature of interior cabin environment, °R
HENV	film coefficient to interior cabin environment, Btu/ft ² -hr-°R
FENV	view factor and emissivity product for radiative heat transfer to cabin interior
QLØSS	boundary condition between last node of the backup structure and cabin environment
=0	adiabatic surfaces
=+1	radiation and/or convective loss
TEST2	determines the proper heat shield initial temperature distribution
=0	constant, uniform initial temperature distribution
=-1	arbitrary initial temperature distribution
=+1	linear temperature distribution
TEMPI	temperature to be used when constant temperature distribution option is used, °R
TXØ	initial temperature at front surface of heat shield to be used in computing initial linear temperature gradient, °R
TEM DI	arbitrary temperature distribution values, to be used only if TEST2 is negative, °R

NHP	number of points in enthalpy - temperature curve fit
HX	enthalpy values in enthalpy - temperature table, Btu/lbm
TW	corresponding temperature values in enthalpy - temperature table, °R

Input Data Card Preparation

The input data are given in the following order. Each number in the following listing refers to a separate record and must begin on a new data card. The input data have been grouped, where possible, into various sections dealing with a particular part of the input, that is, ablation material properties, trajectory data, backup structure, et cetera. This grouping permits the use of a minimum number of input cards for running successive problems. The title card as described in the input nomenclature controls the input for successive problems.

1. The first data card contains the value of NCASE. NCASE is an integer (I5 format) and must end in column 5. This card tells how many problems are to be run and is entered only once at the start of the data deck.

2. Columns 1 to 72 of the second data card contain any title or identification information desired; any alphanumeric character may be used. This card is printed at the top of the first page of the output. This card must be included in all successive problems to be run.

(a) Problem time section

3. TITLE card - if blank, cards 4 and 5 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 6.

4. This record contains, in the following order, TLIM, TINT, NPTT, and NPLØT. TLIM and TINT are entered as floating-point numbers and must end in columns 12 and 24. NPTT and NPLØT are integers entered with an I5 format and must end in column 30 and 35.

5. Start entering the values of TTABLE, DELTT, IPRC. TTABLE and DELTT are floating-point numbers and must end in columns 12 and 24. IPRC is entered as integer with an I5 format and must end in column 30. Use as many cards as required to enter NPTT values.

(b) Heating rate factors section

6. TITLE card - if blank, card 7 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 8.

7. Enter the $FC\phi NV$ and $FRAD$. These numbers are entered as floating-point numbers and must end in columns 12 and 24.

(c) Ablation material section

8. TITLE card — if blank, cards 9 to 18 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 19.

9. HEADNG card — any alphanumeric characters in columns 1 to 72. Records 9 to 18 contain input data for the ablation material.

10. Enter $TABL$, $TCHAR$, $TREC$, $RH\phi V$, $RH\phi C$, and $FBL\phi W$. These numbers are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72.

11. Enter EMV , EMC , $H300$, VL , HV , and VPT . Use the same format as card 10.

12. Enter FV , TV , $CHARK$, $CHARC$, $ABLK$, and $ABLC$. Use the same format as card 10.

13. This card contains, in the following order, NP , NKC , NPC , NKV , $NCPV$, and $NREC$. These numbers are fixed-point integers and must end in columns 5, 10, 15, 20, 25, and 30. An I5 format is used to read in these numbers.

14. Start entering the curve of TKC versus XKC , with the values of TKC ending in columns 12, 36, and 60. The corresponding values of XKC must end in columns 24, 48, and 72; for example, three TKC - XKC points are contained on one card. The numbers are entered as floating-point numbers. Use as many cards as required to enter NKC points on the curve.

15. Start entering the curve of $TCPC$ versus CPC with the values of $TCPC$, ending in columns 12, 36, and 60. The corresponding values of CPC must end in columns 24, 48, and 72; for example, three $TCPC$ - CPC points are contained on one card. The numbers are entered as floating-point numbers. Use as many cards as required to enter the NPC points on the curve.

16. Start entering the curve of TKV versus XKV with the values of TKV ending in columns 12, 36, and 60. The corresponding values of XKV must end in columns 24, 48, and 72; for example, three TKV - XKV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter the NKV points on the curve.

17. Start entering the curve of $TCPV$ versus CPV with the values of $TCPV$, ending in columns 12, 36, and 60. The corresponding values of CPV must end in columns 24, 48, and 72; for example, three $TCPV$ - CPV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter $NCPV$ points on the curve.

18. Start entering the curve of TS versus SR with the values of TX , ending in columns 12, 36, and 60. The corresponding values of SR must end in columns

24, 48, and 72; for example, three TS-SR points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NREC points on the curve.

(d) Trajectory data section

19. TITLE card - if blank, cards 20 to 22 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 23.

20. HEADNG card - any alphanumeric characters in columns 1 to 72. Records 21 and 22 contain trajectory input data.

21. Enter NTRAPT. This number is an integer and must end in column 5. An I5 format is used to read in this number.

22. Start entering the trajectory data in the following order: TIME, QCØN, QRAD, VEL. These values are entered as floating-point numbers and must end in columns 12, 24, 36, and 48. There are four trajectory data points on one card. Use as many cards as required to enter NTRAPT points in the trajectory.

(e) Backup structure section

23. TITLE card - if blank, cards 24 to 31 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 32.

24. Enter NMB, NPBS, and BL. These three values must end in columns 5, 10, and 24. NMB and NPBS are integers and are read in under an I5 format. BL is a floating-point number.

25. Enter the values of XNPM. XNPM is in floating-point form and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

26. Enter the values of NKPB and NCPB. These numbers are integers and NKPB must end in columns 5, 15, 25, 35, and 45; and the corresponding values of NCPB must end in columns 10, 20, 30, 40, and 50. An I5 format is used to read these values. Five NKPB-NCPB values are contained on one card. Use as many cards as are required to enter NMB points.

27. XIDNT card - any alphanumeric characters in columns 1 to 72. This card contains a description of each backup material.

28. Start entering the curve of TXK versus XK with the values of TXK, ending in columns 12, 36, and 60. The corresponding values of XK must end in columns 24, 48, and 72; for example, three TXK-XK points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NKPB points on the curve.

29. Start entering the curve of TCP versus CPX with the values of TCP, ending in columns 12, 36, and 60. The corresponding values of CPX must end in columns 24, 48, and 72; for example, three TCP-CPX points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NCPB points on the curve. Repeat records 27, 28, and 29 until the properties for NMB materials have been entered. The maximum number for NMB is 12.

30. Start entering the following values in order: RHØBX, XBM, EMFB, and EMBB. These values are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

31. Start entering the following values in order: H, GAPX, FTEST, and BTEST. These values are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

(f) Interior environment section

32. TITLE card - if blank, cards 33 and 34 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 35.

33. HEADNG card - any alphanumeric characters in columns 1 to 72. Record 35 contains properties of environment.

34. Enter the following: TENV, HENV, FENV, and QLØSS. The values are entered as floating-point numbers and must end in columns 12, 24, 36, and 48.

(g) Initial temperature section

35. TITLE card - if blank, records 36 and 37 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record 39.

36. HEADNG card - any alphanumeric characters in columns 1 to 72. Records 37 and 38 contain initial temperature distribution input.

37. Enter TEST2, TEMPI, and TXØ. These values are entered as floating-point numbers and must end in columns 12, 24, and 36.

NOTE: If TEST2 is a negative number, record 38 must be submitted; otherwise, skip to record 39.

38. Enter the arbitrary temperature distribution values, TEMDI. These values are entered as floating points with a 6E12.8 format. Use as many cards as required to enter NP plus NPBS node points.

(h) Enthalpy - temperature section

39. TITLE card - if blank, records 40 and 41 must be submitted; if six asterisks are punched in columns 1 to 6, this is the last data card in the problem input.

40. Enter NHP. This value is an integer and must end in column 5. An I5 format is used to read in this number.

41. Start entering the curve of HX versus TW with the value of HX ending in columns 12, 36, and 60. The corresponding values of TW must end in columns 24, 48, and 72; for example, three HX-TW points are contained on one card. The numbers are entered as floating points. Use as many cards as required to enter NHP points on the curve. Record 41 consists of the last data cards required as input for a problem.

As many successive problems as desired may be run at one time by proper input preparation. STAB II has been designed to save all input information until it is changed by new input data. Therefore, the use of the TITLE control card is very important when running more than one problem and using the input data of previous problems. As shown, each input section starts with a TITLE control card for determining whether new input data are to be used. If any data are changed within a section, then all data cards required for that section must be submitted.

STAB II can also be used for solving one-dimensional transient heat-conduction problems of nonabating materials. The following input parameters must be adhered to:

1. TABL must be greater than the maximum temperature expected during the calculation. Also, $TABL > TCHAR > TREC$.

2. The ablation material must be considered to be the first material in the structure for calculation purposes.

3. The virgin and char properties must be inputted as described above but can have the same values; that is, $XKV = XKC$, $CPC = CPV$, $RH\phi V = RH\phi C$, et cetera.

The following dimensional statements and program limitations should not be violated when preparing the input described above for ablating and non-ablating structure:

1. All property tables can have a maximum of 20 points (i.e., a temperature and specific heat value constitute one point).

2. The surface recession table can have a maximum of 50 points (TS and SR constitute one point).

3. The trajectory table can have a maximum of 300 points (TIME, $QC\phi N$, QRAD, and VEL constitute one point).

4. The ablation material can be broken into a maximum of 50 nodes. The backup structure can consist of up to 12 different materials with a maximum of 10 nodes per material.

5. A minimum of three nodes per material (ablation or backup) must be specified.

6. A minimum of two materials must be specified (ablation material and one backup structure material).

7. Pure conduction only is allowed between the ablation material and the first material in the backup.

8. If any data input is changed in the Ablation Material Section on successive problems, the Ablation Material Section data cards plus the Initial Temperature Section data cards must be submitted.

Program Output Information

The computed results are available in two forms of output: tabular and plot outputs. The tabular output presents the computed results in block type form for each computation step as controlled by the print count control number. As discussed in the preparation of input data, both the computational time step and print control can be varied throughout the running of a problem. Therefore, excessive printed output is avoided, and there is a considerable savings in actual machine computation time. The plot outputs are printed and plotted only when the entire set of problems to be run are completed.

Tabular output. - The program prints a listing of the data input parameters for identification of the problem and ease in identifying any input mistakes. For stacked problems, the program prints only that input information that is changed from the previous problem. The following calculated problem output is printed:

1. Time, sec
2. Cold wall convective heating rate without blowing, $\text{Btu/ft}^2\text{-sec}$
3. Radiative heating rate, $\text{Btu/ft}^2\text{-sec}$
4. Velocity, ft/sec
5. Gas ablation rate, $\text{lbm/ft}^2\text{-hr}$
6. Char ablation rate, $\text{lbm/ft}^2\text{-hr}$
7. Total ablation rate, $\text{lbm/ft}^2\text{-hr}$
8. Surface recession depth from original surface, in.

9. Hot wall convective heating rate without blowing, $\text{Btu/ft}^2\text{-sec}$
10. Temperature distribution in ablation material, $^{\circ}\text{R}$
11. Temperature distribution in backup structure, $^{\circ}\text{R}$

The temperatures printed for the ablation material are for fixed distances from the original surface. These distances are calculated from the initial ablation material thickness and number of nodes in ablation material. For example

let

$$VL = 1.0 \text{ in.}$$

$$NP = 11$$

then

$$\Delta X = \frac{VL}{NP - 1} = 0.1$$

The temperatures will be printed for X distances of 0, 0.1, 0.2, 0.3, et cetera, from the original surface until the surface has receded beyond these fixed distances at which time the node no longer exists and is dropped from the printout. This is illustrated in the following way: let surface recession = 0.26 inch. The first temperature printed then is the surface temperature of the material, located 0.26 inch from the original material surface. The following printed ablation material temperatures are for X distances of 0.3, 0.4, 0.5, ..., 1.0 inch.

The format for the temperature distribution printout is E16.5 with six temperatures printed per line.

Plot output. — The plot output gives the following ablative material performance parameters as a function of time:

1. Surface depth, in.
2. Bondline temperature between ablator and backup structure, $^{\circ}\text{R}$
3. Two selected isotherm depths

These values are also printed in tabular form for ease in checking and replotting of the results. The plotted curves contain all maximum and minimum values of the parameters.

APPENDIX C

PROGRAM IN FORTRAN STATEMENTS

\$IBFTC MAIN	A0000
C	A0010
C STRUCTURES AND MECHANICS DIVISION	A0020
C THERMO-STRUCTURES BRANCH	A0030
C THERMAL PROTECTION SYSTEMS SECTION	A0040
C	A0050
C THIS PROGRAM DETERMINES THE PERFORMANCE OF A CHARRING ABLATOR	A0060
C	A0070
C ANALYSIS AND PROGRAM DEVELOPED BY DONALD M. CURRY * ES32	A0080
C	A0090
DIMENSION ESAVE1(3),ESAVEF2(3),ESAVE3(3).	A0100
DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),	A0110
1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),	A0120
2ORAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)	A0130
3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFB(12),EMBR(12),HXX(12)	A0140
4,GAPX(12),FTFST(12),RTEST(12),TFMDI(200),TX1(200),TX2(200),	A0150
5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),	A0160
6IR2(50),TUL(50),IFM(50),TY(200),A(200),R(200),C(200),n(200),	A0170
7R(50),RHO(50),CP(50),DXR(12),XKR(10,12),CPB(10,12),XMDG(50),	A0180
8YK(50),AB(10,12),RB(10,12),CR(10,12),DB(10,12),SR(10,12),	A0190
9RR1(10,12),RB2(10,12),H(12),S(50),NPM(12)	A0200
DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)	A0210
DIMENSION TIMFP(300),PRFS(300),Xc(50),TX2C(50),XV(50),XDV(50)	A0220
DIMENSION TS(50),SR(50)	A0230
DIMENSION TTABLE(20),DELTT(20),IPRC(20)	A0240
DIMENSION ASAVE1(3),ASAVEF2(3),ASAVE3(3),BSAVE1(3),BSAVE2(3),	A0250
1HSAVE3(3),CSAVE1(3),CSAVE2(3),CSAVE3(3),HFAD(12),	A0260
1DSAVE1(3),DSAVE2(3),DSAVEF3(3)	A0270
DIMENSION XRA(30),YA(30)	A0280
C	A0290
COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XRM,FMBR,	A0300
1FMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTFST,RTEST,TFMDI,TX1,	A0310
2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AR,RR,CR,DB,SR,	A0320
3RR1,RR2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKR,CPB,DXR,DT,XLOST,	A0330
4TABL,TCHAR,TRFC,RHOV,RHOC,FRLow,FMV,EMC,H300,NKC,NCPB,NKV,NCPV,	A0340
5NP,NMR,NPBS,NPF,TEST2,TFMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT	A0350
COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,FRR1,ERR2,	A0360
1FRR3,FRR4,HV,VPT,CHARK,CHARC,ABLK,APLC,XMDC,H	A0370
C	A0380
3000 FORMAT(12A6)	A0390
3001 FORMAT(1X,12A6)	A0400
3002 FORMAT(6E12.8)	A0410
3003 FORMAT(6I5)	A0420
3004 FORMAT(1I5)	A0430
3005 FORMAT(2I5)	A0440
3007 FORMAT(2I5,1E14.8)	A0450
3008 FORMAT(///1X,12A6)	A0460
3009 FORMAT(1H1,1X,12A6)	A0470
3010 FORMAT(4E12.8)	A0480
3011 FORMAT(2E12.8,I6,I5,F13.8,E12.8)	A0490
3012 FORMAT(2E12.8,I6)	A0500
DATA PRVOUS/0545454545454/	A0510
REWIND 11	A0520
STOP=9999.	A0530
READ(5,3003)NCASE	A0540
LPLOT=0	A0550
JCNT=0	A0560

50	NK=1	A0570
	I1=2	A0580
	I2=2	A0590
	I3=2	A0600
	I4=2	A0610
	I5=2	A0620
	I6=2	A0630
	I17=2	A0640
	INT=1	A0650
	XLOST=0.0	A0660
	XMT=0.0	A0670
	XMDT=0.0	A0680
	FRR1=0.0	A0690
	FRR2=0.0	A0700
	FRR3=0.0	A0710
	FRR4=0.0	A0720
	ICT=0	A0730
	ICONT=0	A0740
	XMDC=0.0	A0750
	NKP=1	A0760
	XLSTV=0.0	A0770
	NRS=2	A0780
	FRR5=0.0	A0790
	TPCT=0	A0800
	ICTP=0	A0810
	IPLOT=1	A0820
	NXA=1	A0830
	NXB=1	A0840
	NXC=1	A0850
	NXD=1	A0860
	SAVY3=-100.	A0870
	SAVY4=-100.	A0880
	SX0=0.0	A0890
	SNOT=0.0	A0900
C		A0910
C	GENERAL TITLE OF PROBLEM	A0920
100	READ(5,3000) (HEAD(K),K=1,12)	A0930
	WRITE(6,3009) (HEAD(K),K=1,12)	A0940
	LPL0T=LPL0T+1	A0950
	WRITE (11)(HEAD(I),I=1,12)	A0960
	WRITE(6,110)	A0970
110	FORMAT(//1X,11HINPUT DATA,//)	A0980
	READ(5,3000) (TITLE(L),L=1,12)	A0990
	IF(TITLE(1).EQ.PRVIOUS) GO TO 150	A1000
	READ(5,3011) TLIM,TINT,NPTT,NPLOT,DMP,TDMP	A1010
	READ(5,3012) (TTABLE(I),DFLTT(I),IPRC(I),I=1,NPTT)	A1020
	T=TINT	A1030
	OTS=DFLTT(1)	A1040
	DT=DELTT(1)/3600.0	A1050
	WRITE(6,120) TLIM,TINT,NPTT	A1060
120	FORMAT(1H0,11HTIME LIMIT=,1PE10.4,4X,13HINITIAL TIME=,1PE10.4,4X,5	A1070
	1HNPTT=,I4)	A1080
	WRITE(6,122)	A1090
122	FORMAT(//8X,4HTIME,10X,9HTIME STEP,6X,13HPRINT CONTROL)	A1100
	WRITE(6,124) (TTABLE(I),DFLTT(I),IPRC(I),I=1,NPTT)	A1110
124	FORMAT(5X,1PE10.4,6X,1PE10.4,9X,I4)	A1120
C		A1130

C	LOCATION FACTORS FOR CONVECTIVE AND RADIATIVE HEATING	A1140
150	READ(5,3000) (TITLE(L),L=1,12)	A1150
	IF(TITLE(1).EQ.PRVIOUS) GO TO 200	A1160
	READ(5,3002) FCONV,FRAD	A1170
	WRITE(6,155) FCONV,FRAD	A1180
155	FORMAT(1H0,6HFCONV=,1PE12.5,4X5HFRAD=,1PF12.5/)	A1190
C		A1200
C	PROPERTIES OF ABLATION MATERIAL	A1210
200	READ(5,3000) (TITLE(L),L=1,12)	A1220
	IF(TITLE(1).EQ.PRVIOUS) GO TO 300	A1230
	READ(5,3000) (HEADNG(K),K=1,12)	A1240
	READ(5,3002) TABL,TCHAR,TREC,PHOV,RHOC,FRLow,FMV,EMC,H300,VL,HV,	A1250
	1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC	A1260
	RFA (5,3003) NP,NKC,NCPC,NKV,NCPV,NREC	A1270
	READ(5,3002) (TKC(K),XKC(K),K=1,NKC)	A1280
	READ(5,3002) (TCPC(M),CPC(M),M=1,NCPC)	A1290
	READ(5,3002) (TKV(L),XKV(L),L=1,NKV)	A1300
	READ(5,3002) (TCPV(N),CPV(N),N=1,NCPV)	A1310
	READ(5,3002) (TS(I),SR(I),I=1,NRFC)	A1320
	WRITE(6,3008) (HEADNG(K),K=1,12)	A1330
	WRITE(6,210) TABL,TCHAR,TREC,PHOV,RHOC,FRLow,FMV,EMC,H300,VL,HV,	A1340
	1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC	A1350
210	FORMAT(1H0,5HTABL=,1PF12.5,3X,6HTCHAR=,1PF12.5,3X,5HTREC=,1PE12.5,	A1360
	13X,5HRHOV=,1PF12.5,3X,5HRHOC=,1PF12.5,21X/1X,6HFBLow=,1PF12.5,4X,4	A1370
	2HEMV=,1PE12.5,4X,4HEMC=,1PE12.5,3X,5HH300=,1PF12.5,5X,3HVL=,1PE12.	A1380
	35/4X,3HHV=,1PF12.5,4X,4HVPT=,1PF12.5,5X,3HFV=,1PF12.5,5X,3HTV=,1PE	A1390
	112.5,2X,6HCHARK=,1PF12.5/1X,6HCHARC=,1PF12.5,3X,5HABLK=,1PE12.5,3X	A1400
	2,5HABLC=,1PE12.5/)	A1410
	VL=VL	A1420
	VL=VL/12,0	A1430
	VLV=VL	A1440
	WRITE(6,220) NP,NKC,NCPC,NKV,NCPV,NREC	A1450
220	FORMAT(2X,3HNPC=,1I4,4X,4HNKC=,1I4,4X,5HNPC=,1I4,4X,4HNKV=,1I4,4X,	A1460
	15HNCPV=,1I4,4X,5HNREC=,1I4)	A1470
	WRITE(6,221)	A1480
221	FORMAT(/32X,15HVIRGIN MATERIAL/20X,7HTHERMAL,38X,8HSPFCIFIC/3X,11H	A1490
	1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)	A1500
	KLLL=MIN0(NKV,NCPV)	A1510
	WRITE(6,222) (TKV(L),XKV(L),TCPV(L),CPV(L),L=1,KLLL)	A1520
222	FORMAT(2X,1PE12.5,4X,1PE12.5,18X,1PE12.5,3X,1PE12.5)	A1530
	IF(NKV-NCPV) 223,227,225	A1540
223	KLLLL=KLLL+1	A1550
	WRITE(6,224) (TCPV(L),CPV(L),L=KLLLL,NCPV)	A1560
224	FORMAT(48X,1PF12.5,3X,1PF12.5)	A1570
	GO TO 227	A1580
225	KLLLL=KLLL+1	A1590
	WRITE(6,226) (TKV(L),XKV(L),L=KLLLL,NKV)	A1600
226	FORMAT(2X,1PE12.5,4X,1PE12.5)	A1610
227	WRITE(6,228)	A1620
228	FORMAT(/33X,14HCHAR MATERIAL/20X,7HTHERMAL,38X,8HSPFCIFIC/3X,11H	A1630
	1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)	A1640
	KLLL=MIN0(NKC,NCPC)	A1650
	WRITE(6,222) (TKC(L),XKC(L),TCPC(L),CPC(L),L=1,KLLL)	A1660
	IF(NKC-NCPC) 230,235,232	A1670
230	KLLLL=KLLL+1	A1680
	WRITE(6,224) (TCPV(L),CPV(L),L=KLLLL,NCPV)	A1690
	GO TO 235	A1700

232	KLLLL=KLLI+1	A1710
	WRITE(6,226) (TKC(L),XKC(I),L=KLI,LL,NKC)	A1720
235	WRITE(6,240)	A1730
240	FORMAT(/28X,23HSURFACE RECFSSION TABLE//25X,11HTFMPERATURE,8X,11H	A1740
	1SR - 1N/SEC)	A1750
	WRITE(6,245) (TS(I),SR(I),I=1,NRFC)	A1760
245	FORMAT(24X,1PF12.5,7X,1PF12.5)	A1770
C		A1780
C	PROPERTIES OF TRAJECTORY	A1790
300	READ(5,3000) (TITLE(L),L=1,12)	A1800
	IF(TITLE(1),FO.PRVIOUS) GO TO 400	A1810
	READ(5,3000) (HEADNG(L),I=1,12)	A1820
	READ(5,3004) NTRAPT	A1830
	READ(5,3010) (TIME(K),QCON(K),GRAD(K),VFL(K),K=1,NTRAPT)	A1840
	WRITE(6,3008) (HEADNG(L),I=1,12)	A1850
	WRITE(6,310) NTRAPT	A1860
310	FORMAT(1H0,27H NO. OF TRAJECTORY POINTS =,1I4)	A1870
	WRITE(6,320)	A1880
320	FORMAT(/8X,4HTIME,8X,12HQ CONVECTIVE,4X,11HQ RADIATIVE,7X,8HVELOC	A1890
	1TTY)	A1900
	WRITE(6,330) (TIME(K),QCON(K),GRAD(K),VFL(K),K=1,NTRAPT)	A1910
330	FORMAT(1F4E16,5)	A1920
C		A1930
C	PROPERTIES OF BACK-UP STRUCTURE	A1940
400	READ(5,3000) (TITLE(L),L=1,12)	A1950
	IF(TITLE(1),FO.PRVIOUS) GO TO 500	A1960
	WRITE(6,410)	A1970
410	FORMAT(/10X,31H PROPERTIES OF BACKUP STRUCTURE/)	A1980
	READ(5,3007) NMP,NPRS,BL	A1990
	READ(5,3002) (XNPM(K),K=1,NMR)	A2000
	READ(5,415) (NKPBI(I),NCPBI(I),I=1,NMR)	A2010
415	FORMAT(10J5)	A2020
	DO 420 K=1,NMP	A2030
	NPM(K)=XNPM(K)+0.00000002	A2040
420	CONTINUE	A2050
	WRITE(6,425) NMP,NPRS,BL	A2060
425	FORMAT(/4X,35HNO. OF MATERIALS IN BACK-UP SHIELD=,1I4/4X,40HTOTAL	A2070
	1NUMBER OF NODES IN BACK-UP SHIELD=,1I4/4X,28HTHICKNESS OF BACK-UP	A2080
	2SHIELD=,1PE12.5//)	A2090
	BL=BL/12.0	A2100
	DO 440 I=1,NMR	A2110
	LK=NKPBI(I)	A2120
	LCP=NCPBI(I)	A2130
	READ(5,3000) ((XIDNT(K,I)),K=1,12)	A2140
	READ(5,3002) ((TXK(J,I),XK(J,I)),J=1,LK)	A2150
	READ(5,3002) ((TCP(J,I),CPX(J,I)),J=1,LCP)	A2160
	WRITE(6,432) (XIDNT(K,I),K=1,12)	A2170
432	FORMAT(/12A6)	A2180
	WRITE(6,433)	A2190
433	FORMAT(/20X,7HTHERMAL,38X,8HSPECIFIC/3X,11HTFMPERATURE,4X,12HCOND	A2200
	1UCTIVITY,19X,11HTFMPERATURE,7X,4HHEAT)	A2210
	KLLL=MIN0(LK,LCP)	A2220
	DO 434 N=1,KLLL	A2230
	WRITE(6,222) (TXK(N,I),XK(N,I),TCP(N,I),CPX(N,I))	A2240
434	CONTINUE	A2250
	IF(LK-LCP) 435,440,437	A2260
435	KLLLL=KLLI+1	A2270

DO 436 N=KLLLL, LCP	A2280
WRITE(6,224) (TCP(N,T),CPX(N,T))	A2290
436 CONTINUE	A2300
GO TO 440	A2310
437 KLLLL=KLLLL+1	A2320
DO 438 N=KLLLL, LK	A2330
WRITE(6,226) (TXK(N,T),XK(N,I))	A2340
438 CONTINUE	A2350
440 CONTINUE	A2360
READ(5,3002) (RHORX(L),XRM(L),EMFR(L),EMRB(L),L=1,NMR)	A2370
READ(5,3002) (H(J),GAPX(J),FTEST(J),BTFT(J),J=1,NMR)	A2380
WRITE(6,450)	A2390
450 FORMAT(//55X,10HEMISSIVITY/8X,8HMATERIAL,5X,7HDENSITY,7X,9HTHICKN	A2400
1FSS,7X,5HFRONT,9X,4HBACK,7X,14HNODES/MATERIAL/)	A2410
DO 460 LLJ=1,NMR	A2420
WRITE(6,455) LLJ,RHORX(LLJ),XPM(LLJ),FMFR(LLJ),FMRB(LLJ),XNPM(LLJ)	A2430
455 FORMAT(11X,11,8X,1PF10.4,4X,1PF10.4,4X,1PF10.4,4X,1PF10.4,6X,1PF1	A2440
10.4/)	A2450
460 CONTINUE	A2460
WRITE(6,465)	A2470
465 FORMAT(//4X,60HADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP	A2480
1STRUCTURE//11X,8HMATERIAL,5X,16HFILM COEFFICIENT,5X,13HGAP THICKNE	A2490
2SS,8X,5HFTST,13X,5HBTST)	A2500
DO 480 J=1,NMR	A2510
WRITE(6,470) J, H(J),GAPX(J),FTEST(J),BTFT(J)	A2520
470 FORMAT(13X,11,12X,1PF10.4,9X,1PF10.4,7X,1PF11.4,7X,1PF11.4/)	A2530
480 CONTINUE	A2540
C	A2550
C PROPERTIES OF ENVIRONMENT	A2560
500 READ(5,3000) (TITLE(L),L=1,12)	A2570
IF(TITLE(1).EQ.PRVIOUS) GO TO 600	A2580
READ(5,3000) (HEADNG(L),L=1,12)	A2590
READ(5,3002) TENV,HFENV,FFNV,QLOSS	A2600
WRITE(6,3008) (HEADNG(L),L=1,12)	A2610
WRITE(6,520) TENV,HFENV,FFNV,QLOSS	A2620
520 FORMAT(/4X,12HTEMPERATURE=,1PF12.5,4X,17HFILM COEFFICIENT=,1PF12.5	A2630
1.4X,12HVIFW FACTOR=,1PF12.5,4X,7H0 LOST=,1PF12.5)	A2640
C	A2650
C INITIAL TEMPERATURE DISTRIBUTION	A2660
600 READ(5,3000) (TITLE(L),L=1,12)	A2670
IF(TITLE(1).EQ.PRVIOUS) GO TO 700	A2680
READ(5,3000) (HEADNG(L),L=1,12)	A2690
NPF=NP+NPRS	A2700
TL=VL+BL	A2710
XNP=NP	A2720
DX=VL/(XNP-1.0)	A2730
DX=DX	A2740
READ(5,3002) TEST2,TFMPI,TX0	A2750
IF(TEST2) 610,620,620	A2760
610 READ(5,3002) (TEMPI(K),K=1,NPF)	A2770
DO 615 K=1,NPF	A2780
TX1(K)=TEMPI(K)	A2790
TX2(K)=TX1(K)	A2800
TUL1(K)=TX1(K)	A2810
TUL2(K)=TX1(K)	A2820
615 CONTINUE	A2830
I=NP+1	A2840

DO 619 I=1,NMR	A2850
LN=NPM(I)	A2860
DO 617 J=1,LN	A2870
TX2T(J,I)=TFMDI(L)	A2880
I=L+1	A2890
617 CONTINUE	A2900
619 CONTINUE	A2910
GO TO 625	A2920
620 CALL TEMPD	A2930
625 WRITE(6,3008) (HEADNG(L),I=1,12)	A2940
IF(TEST2) 630,635,640	A2950
630 WRITE(6,632)	A2960
632 FORMAT(4X,52HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS ARBITRARY/	A2970
1)	A2980
WRITE(6,633) (TFMDI(K),K=1,NPF)	A2990
633 FORMAT(1PE12.5)	A3000
GO TO 645	A3010
635 WRITE(6,637) TEMPI	A3020
637 FORMAT(/4X,64HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM	A3030
1AND EQUAL TO ,1PE10.4/)	A3040
GO TO 645	A3050
640 WRITE(6,641)	A3060
641 FORMAT(4X,54HLINEAR TEMPERATURE DISTRIBUTION ASSUMED IN HEAT SHIEL	A3070
1D/)	A3080
WRITE(6,633) (TFMDI(L),L=1,NPF)	A3090
645 IF(DMP) 700,700,646	A3100
646 WRITE(6,647)	A3110
647 FORMAT(/)	A3120
648 WRITE(6,649) (TX1(L),TX2(L),L=1,NPF)	A3130
649 FORMAT(2X,1PF12.5,4X,1PF12.5)	A3140
WRITE(6,650)	A3150
650 FORMAT(/)	A3160
C	A3170
C ENTHALPY AS A FUNCTION OF TEMPERATURE	A3180
700 READ(5,3000) (TITLE(L),L=1,12)	A3190
IF(TITLE(1).EQ.PRVIOUS) GO TO 725	A3200
READ(5,3004) NHP	A3210
READ(5,3002) (HX(K),TW(K),K=1,NHP)	A3220
725 DO 728 I=1,NP	A3230
TP(I)=0	A3240
TP1(I)=0	A3250
TP2(I)=0	A3260
TFM(I)=0	A3270
XMDG(I)=0.0	A3280
728 CONTINUE	A3290
WRITE(6,730)	A3300
730 FORMAT(1H1,12HOUTPUT DATA./)	A3310
XC(1)=0.0	A3320
DO 740 I=2,NP	A3330
XC(I)=XC(I-1)+DX	A3340
740 CONTINUE	A3350
750 IF(T-TIME(NK)) 765,770,760	A3360
760 NK=NK+1	A3370
IF(NK-NTRAPT) 750,750,762	A3380
762 WRITE(6,763) NK	A3390
763 FORMAT(1H0,33H THE VALUE OF NK IS IN ERROR, NK=,1I4)	A3400
GO TO 905	A3410

765	IF(NK-2) 762,766,766	A3420
766	QCONX=QCON(NK-1)+((QCON(NK)-QCON(NK-1))/(TIME(NK)-TIME(NK-1)))	A3430
	1*(T-TIME(NK-1))	A3440
	QCONX=FCONV*QCONX	A3450
	QRADX=QRAD(NK-1)+((QRAD(NK)-QRAD(NK-1))/(TIME(NK)-TIME(NK-1)))	A3460
	1*(T-TIME(NK-1))	A3470
	QRADX=FRAD*QRADX	A3480
	VFLX=VEL(NK-1)+((VEL(NK)-VEL(NK-1))/(TIME(NK)-TIME(NK-1)))	A3490
	1*(T-TIME(NK-1))	A3500
	GO TO 775	A3510
770	QCONX=FCONV*QCON(NK)	A3520
	QRADX=FRAD*QRAD(NK)	A3530
	VFLX=VEL(NK)	A3540
C		A3550
C	COMPUTE HEAT BLOCKAGE AT FRONT SURFACE	A3560
775	IF(I17-1) 778,778,776	A3570
776	IF(I17-NHP) 777,777,778	A3580
777	IF(TX2(INT)-TW(I17)) 782,788,780	A3590
778	WRITE(6,779) TX2(INT)	A3600
779	FORMAT(1H0,80H THE RANGE OF THE ENTHALPY-TEMPERATURE CURVE FIT WAS	A3610
	1FXCEEDED AT A TEMPERATURE OF,1E10.4)	A3620
	GO TO 905	A3630
780	I17=I17+1	A3640
	GO TO 776	A3650
782	IF(TX2(INT)-TW(I17-1)) 784,788,786	A3660
784	I17=I17-1	A3670
	GO TO 775	A3680
786	HW=HX(I17-1)+((HX(I17)-HX(I17-1))/(TW(I17)-TW(I17-1)))	A3690
	1*(TX2(INT)-TW(I17-1))	A3700
	GO TO 789	A3710
788	HW=HX(I17)	A3720
789	HTX=H300+((VFI X**2)/50056.5)	A3730
	QBLOCK=(FRLow*XMDG(INT))*(HTX-HW)/3600.0	A3740
C		A3750
C	COMPUTE HEAT IN DUE TO SURFACE COMBUSTION	A3760
	XMD0=XMDC	A3770
	CALL OXIUT(XMD0,QOXID)	A3780
C		A3790
C	COMPUTE Q-HOT WALL	A3800
	IF(TDMP.E0.0.) GO TO 4001	A3810
	IF(T.GE.TDMP) DMP=1.0	A3820
4001	Z=(HTX-HW)/(HTX-H300)	A3830
	IF(Z-1.0) 790,792,793	A3840
790	IF(Z) 791,791,793	A3850
791	QHW=0.0	A3860
	GO TO 1790	A3870
792	QHW=QCONX	A3880
	GO TO 1790	A3890
793	QHW=Z*QCONX	A3900
1790	ZZZ=(QHW-QBLOCK)/QHW	A3910
	IF(ZZZ-0.2) 1798,1798,1794	A3920
1798	QBLOCK=0.8*QHW	A3930
C		A3940
C	NET HEAT INTO FRONT SURFACE	A3950
1794	IF(IEM(INT)) 795,795,797	A3960
795	IF(TX2(INT)-TCHAR) 796,796,797	A3970
796	FMX=EMV	A3980

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797 GO TO 798
IFM(INT)=1
FMX=EMC
798 QIN=QRADX+QHW+QOXID-QRLOCK-(4.8333E-13)*FMX*FV*(TX2(INT)**4)-
1(TV**4)
IF(DMP) 804,804,800
800 WRITE(6,801)
801 FORMAT(///)
WRITE(6,802) QCONX,QRADX,VELX,HTX,HX,Z,QRLOCK,QHW,QOXID,QIN
802 FORMAT(1X,6HQCONX=,1PF12.5,2X,6HQRADX=,1PF12.5,2X,5HVFLX=,1PF12.5,
12X,4HHTX=,1PF12.5,2X,3HHW=,1PF12.5/1X,2H7=,1PF12.5,2X,7HQRLOCK=,1P
2F12.5,2X,4HQHW=,1PF12.5,2X,6HQOXID=,1PF12.5,2X,4HQIN=,1PF12.5/)
804 QIN=QIN*3600.0
C
C CHECK FOR FRONT SURFACE RECESSION (CHAR LAYER REMOVAL)
CALL RECESS(XMDC,XLOST,TRFC,DT,PHOC,TS,SR,TX2(1),NREC,NRS,ERR5,SX0
1,SDOT,DMP)
IF(ERR5) 8050,8050,905
8050 VLV=VLV-XLOST
XI STV=XLSTV+XLOST
XI STI=XLSTV*12.0
DXV=VLV/(XNP-1.0)
XV(1)=0.0
DO 1780 I=2,NP
XV(I)=XV(I-1)+DXV
1780 CONTINUE
DX=DXV
IF(ERR4) 806,806,805
805 GO TO 905
806 CALL COEFF(NPFT,SDOT)
IF(DMP) 8069,8069,8061
8061 WRITE(6,8062)
8062 FORMAT(1X,23H COEFFICIENTS FOR SWUFT/)
DO 8066 I=1,NPFT
WRITE(6,8064) A(I),B(I),C(I),D(I),I
8064 FORMAT(1H0,5HA(I)=,1PF12.5,2X,5HB(I)=,1PF12.5,2X,5HC(I)=,1PF12.5,2
1X,5HD(I)=,1PF12.5,2X,2HI=,I3)
8066 CONTINUE
8069 IF(ERR2) 807,807,805
807 IF(ERR3) 810,810,808
808 WRITE(6,809) IKK
809 FORMAT(1H0,18H THE VALUE OF IKK=,I4)
GO TO 905
810 CALL SWUFT(A,B,C,D,TY,NPFT,DMP)
827 DO 828 I=1,NP
TX1(I)=TX2(I)
TX2(I)=TY(I)
828 CONTINUE
CALL DON2(XLOST,XV,TX2,NP,XC,TX2C,XDV,KKV,XLSTV,DXV)
830 CALL ABLATE
XMDT=XMDG(INT)+XMDC
LT=NP+1
DO 1815 I=1,NMB
LLT=NPM(1)
IF(I.FQ.1) GO TO 1812
IF(GAPX(I-1).FQ.0.) GO TO 1812
KKT=1

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A3990
A4000
A4010
A4020
A4030
A4040
A4050
A4060
A4070
A4080
A4090
A4100
A4110
A4120
A4130
A4140
A4150
A4160
A4170
A4180
A4190
A4200
A4210
A4220
A4230
A4240
A4250
A4260
A4270
A4280
A4290
A4300
A4310
A4320
A4330
A4340
A4350
A4360
A4370
A4380
A4390
A4400
A4410
A4420
A4430
A4440
A4450
A4460
A4470
A4480
A4490
A4500
A4510
A4520
A4530
A4540
A4550

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GO TO 1813	A4560
1812 KKT=2	A4570
1813 DO 1815 J=KKT,LLT	A4580
TX2T(J,I)=TY(LT)	A4590
LT=LT+1	A4600
1815 CONTINUE	A4610
DO 1819 I=1,NMB	A4620
IF(I,FQ,1) GO TO 1816	A4630
IF(GAPX(I-1),FQ,0.) GO TO 1817	A4640
GO TO 1819	A4650
1816 TX2T(1,1)=TY(NP)	A4660
GO TO 1819	A4670
1817 LX=NPM(I-1)	A4680
TX2T(1,I)=TX2T(LX,I-1)	A4690
1819 CONTINUE	A4700
LM=NP+1	A4710
DO 833 I=1,NMR	A4720
L7=NPM(I)	A4730
DO 833 J=1,L7	A4740
TX2(LM)=TX2T(J,I)	A4750
LM=LM+1	A4760
833 CONTINUE	A4770
DO 5834 I=2,NPTT	A4780
IF(T-TTABLE(I)) 5835,5835,5834	A4790
5835 DTS=DELT(I-1)	A4800
IPRCT=IPRC(I-1)	A4810
DT=DELT(I-1)/3600.0	A4820
GO TO 5836	A4830
5834 CONTINUE	A4840
DTS=DELT(NPTT)	A4850
IPRCT=IPRC(NPTT)	A4860
DT=DELT(NPTT)/3600.0	A4870
5836 ICT=ICT+1	A4880
5838 VLTEM=SAVY3	A4890
CALL ISO1HM(XV, TX2, 1060., NP, SAVFIT)	A4900
SAVFIT=SAVFIT+XLSTV	A4910
IF(SAVY3,LT,SAVFIT) SAVY3=SAVFIT	A4920
IF(VLTEM,FQ,SAVY3) GO TO 839	A4930
SAVX=T	A4940
SAVY1=XLSTI	A4950
SAVY2=TX2(NP)	A4960
CALL ISO1HM(XV, TX2, 1460., NP, SAVY4)	A4970
839 RI TEM=SAVY4X	A4980
CALL ISO1HM(XV, TX2, 1460., NP, WEKEFP)	A4990
WEKEFP=WEKEFP+XLSTV	A5000
IF(SAVY4X,LT,WEKEFP) SAVY4X=WEKEFP	A5010
IF(BLTEM,FQ,SAVY4X) GO TO 838	A5020
SAVEXX=T	A5030
SAVY1X=XLSTI	A5040
SAVY2X=TX2(NP)	A5050
CALL ISO1HM(XV, TX2, 1060., NP, SAVY3X)	A5060
838 CONTINUE	A5070
IF(IPRCT=ICT) 835,835,840	A5080
835 WRITE(6,837) T,QCONX,QRADY,VEL X,XMDG(INT),XMDC,XMDT,XLSTI,QHW	A5090
837 FORMAT(1H0,5HTIME=,	A5100
1 1PF12.5,2X,12H0CONVECTIVE=,1PF12.5,2X,11HORADIAT	A5110
1IVE=,1PE12.5,2X,9HVFLOCITY=,1PE12.5/1X,18HGAS APLATION RATE=,1PF12	A5120

2.5,2X,19HCHAR ABLATION RATE=,1PE12.5,2X,20HTOTAL ABLATION RATE=,1P	A5130
3F12.5/1X,16HRECESSION DEPTH=,1PE12.5,2X,10HQHOT WALL=,1PE12.5)	A5140
840 T=T+DTS	A5150
841 IF(NPLOT.NE.1) GO TO 842	A5160
CALL SAVE(ASAVE1,ASAVE2,ASAVE3,USEA,NXA,XLSTI,DTS,TLIM,T,VALUEA)	A5170
CALL SAVE(BSAVE1,BSAVE2,BSAVE3,USEB,NXB,TX2(NP),DTS,TLIM,T,VALUEB)	A5180
CALL ISOTHM(XV,TX2,1060.,NP,Y3)	A5190
CALL SAVE(CSAVE1,CSAVE2,CSAVE3,USEC,NXC,Y3,DTS,TLIM,T,VALUEC)	A5200
CALL ISOTHM(XV,TX2,1460.,NP,Y4)	A5210
CALL SAVE(DSAVE1,DSAVE2,DSAVE3,USED,NXD,Y4,DTS,TLIM,T,VALUED)	A5220
IF(USFA.NF.0.0)GO TO 9842	A5230
IF(USFB.NF.0.0)GO TO 9842	A5240
IF(USEC.NF.0.0)GO TO 9842	A5250
IF(USFD.NF.0.0)GO TO 9842	A5260
GO TO 9843	A5270
9842 XPL0T=T-DTS	A5280
YPL0T1=VALUEA	A5290
IF(USFA.NF.0.0)YPL0T1=USFA	A5300
YPL0T2=VALUEB	A5310
IF(USFB.NF.0.0)YPL0T2=USFB	A5320
YPL0T3=VALUEC	A5330
IF(USEC.NF.0.0)YPL0T3=USEC	A5340
YPL0T4=VALUED	A5350
IF(USFD.NF.0.0)YPL0T4=USFD	A5360
WRITE (11)XPL0T,YPL0T1,YPL0T2,YPL0T3,YPL0T4	A5370
9843 IF(ICTP.NF.0) GO TO 842	A5380
ICTP=1	A5390
XPL0T=T	A5400
YPL0T1=XLSTI	A5410
YPL0T2=TX2(NP)	A5420
CALL ISOTHM(XV,TX2,1060.,NP,YPL0T3)	A5430
CALL ISOTHM(XV,TX2,1460.,NP,YPL0T4)	A5440
WRITE (11)XPL0T,YPL0T1,YPL0T2,YPL0T3,YPL0T4	A5450
842 IF(IPRCT-ICT) 845,845,900	A5460
845 WRITE(6,850) T	A5470
IPCT=IPCT+1	A5480
IF(IPCT.EQ.2)IPCT=0	A5490
IF(IPCT.EQ.0)ICTP=0	A5500
850 FORMAT(1H0,72HTEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END 0	A5510
1F THE TIME STEP, T= ,1PE12.5,1X,7HSECONDS//)	A5520
WRITE(6,860)	A5530
860 FORMAT(4X,49HTEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL//)	A5540
KKV=KKV+1	A5550
WRITE(6,862) (TX2C(I),I=1,KKV)	A5560
862 FORMAT(6X,1PE12.5,1P5F16.5)	A5570
IJ=NP+1	A5580
WRITE(6,864)	A5590
864 FORMAT(//4X,40HTEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE//	A5600
1)	A5610
WRITE(6,862) (TX2(I),I=IJ,NPF)	A5620
WRITE(6,865)	A5630
865 FORMAT(//)	A5640
ICT=0	A5650
900 CONTINUE	A5660
IF(T-TLIM) 750,750,905	A5670
905 IF(NPLOT.NE.1) GO TO 909	A5680
XAVY3=SAVY3-SAVY1/12.	A5690

XAVY4X=SAVY4X-SAVY1X/12.	A5700
IF(SAVX.EQ.XPLOT)GO TO 9005	A5710
WRITE(11)SAVX,SAVY1,SAVY2,XAVY3,SAVY4	A5720
9005 IF(SAVEXX.EQ.XPLOT)GO TO 9006	A5730
SAV4I=SAVY4X*12.	A5760
9006 SAV3I=SAVY3*12.	A5750
WRITE(11)SAVEXX,SAVY1X,SAVY2X,SAVY3X,XAVY4X	A5740
WRITE(6,929)SAV3I,SAV4I	A5770
929 FORMAT(1H0,23HMAXIMUM 1060 ISOTHERM =E16.8,2X23HMAXIMUM 1460 ISOTH	A5780
1FRM =E16.8)	A5790
WRITE(11)STOP,STOP,STOP,STOP,STOP	A5800
909 IF(LPLOT.NE.NCASE)GO TO 911	A5810
DATA FND/6H FND /	A5820
WRITE(11)FND,FND,FND,FND,FND,FND,FND,FND,FND,FND,FND	A5830
QUIT=8888.	A5840
WRITE(11)QUIT,QUIT,QUIT,QUIT,QUIT	A5850
FND FILE 11	A5860
REWIND 11	A5870
911 IF(TEST2) 910,930,930	A5880
910 DO 920 JJK=1,NPF	A5890
TX1(JJK)=TEMPT(JJK)	A5900
TX2(JJK)=TX1(JJK)	A5910
TUL1(K)=TX1(K)	A5920
TUL2(K)=TX1(K)	A5930
920 CONTINUE	A5940
IL=NP+1	A5950
DO 926 I=1,NMR	A5960
ILN=NPM(I)	A5970
DO 924 J=1,ILN	A5980
TX2T(J,I)=TEMPI(IL)	A5990
IL=IL+1	A6000
924 CONTINUE	A6010
926 CONTINUE	A6020
GO TO 940	A6030
930 CALL TEMPD	A6040
940 T=TINT	A6050
DX=DXX	A6060
NTS=DFLTT(1)	A6070
NT=DELT(1)/3600.0	A6080
VLV=VL	A6090
GO TO 50	A6100
END	A6110

\$IBFTC COEF	B0000
C THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF THE MATRIX	B0010
SUBROUTINE COEFF(NPFT,SDOT)	B0020
C	B0030
DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),	B0040
1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),	B0050
2QRAD(300),VEL(300),XNPM(12),NKP(12),NCPB(12),TXK(20,12),XK(20,12)	B0060
3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBB(12),HXX(12)	B0070
4,GAPX(12),FTEST(12),BTEST(12),TEMPI(200),TX1(200),TX2(200),	B0080
5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),	B0090
6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),	B0100
7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),	B0110
8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),	B0120
9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)	B0130
DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)	B0140
C	B0150
COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,	B0160
1EMFB,NKP,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMPI,TX1,	B0170
2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,	B0180
3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,	B0190
4TABL,TCHAR,TREC,RHOV,RHOC,FBLow,EMV,EMC,H300,NKC,NPC,NKV,NCPV,	B0200
5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT	B0210
COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,	B0220
1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H	B0230
C	B0240
CALL PROP	B0250
YNP=NP	B0260
S(INT)=(RHO(INT)*DX*CP(INT))/(2.0*DT)	B0270
R(INT)=(1.0)/((DX/2.0)*((1.0/YK(INT)))+(1.0/YK(INT+1))))	B0280
A(INT)=0.0	B0290
B(INT)=(-(XMDG(INT)+XMDC)*CP(INT)+S(INT)+R(INT)-RHO(INT)*CP(INT)	B0300
1*(SDOT/(2.0*(YNP-1.0))))	B0310
C(INT)=XMDG(INT+1)*CP(INT+1)+R(INT)+RHO(INT+1)*CP(INT+1)*SDOT	B0320
1*((YNP-1.5)/(YNP-1.0))	B0330
D(INT)=(-(QIN+S(INT)*TX2(INT)))+(XMDG(INT)-XMDG(INT+1))*HV	B0340
NPP=NP-1	B0350
JNT=INT+1	B0360
DO 10 I=JNT,NPP	B0370
XI=I	B0380
S(I)=(RHO(I)*DX*CP(I))/DT	B0390
R(I)=(1.0)/((DX/(2.0*YK(I)))+(DX/(2.0*YK(I+1))))	B0400
A(I)=R(I-1)	B0410
B(I)=(-(XMDG(I)*CP(I)+R(I-1)+R(I)+S(I)+RHO(I)*CP(I)*SDOT*((YNP-XI	B0420
1-0.5)/(YNP-1.0))))	B0430
C(I)=XMDG(I+1)*CP(I+1)+R(I)+RHO(I+1)*CP(I+1)*SDOT*((YNP-XI-0.5)	B0440
1/(YNP-1.0))	B0450
D(I)=(-(S(I)*TX2(I)))+(XMDG(I)-XMDG(I+1))*HV	B0460
10 CONTINUE	B0470
R(NP)=(1.0)/((DXB(1)/(2.0*XKB(1,1)))+(DXB(1)/(2.0*XKB(2,1))))	B0480
S(NP)=(RHO(NP)*DX*CP(NP)+RHOBX(1)*CPB(1,1)*DXB(1))/(2.0*DT)	B0490
A(NP)=R(NP-1)	B0500
B(NP)=(-(XMDG(NP)*CP(NP)+R(NP-1)+R(NP)+S(NP)))	B0510
C(NP)=R(NP)	B0520
D(NP)=(-(S(NP)*TX2(NP)))+(XMDG(NP)*HV	B0530
DO 200 I=1,NMB	B0540
IF(I-1) 20,20,30	B0550
20 AB(1,I)=A(NP)	B0560
BB(1,I)=B(NP)	B0570
CB(1,I)=C(NP)	B0580
DB(1,I)=D(NP)	B0590

GO TO 65	B0600
30 L=NPM(I-1)	B0610
IF(FTEST(I)) 45,40,45	B0620
40 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I)+RHOBX(I-1)*CPB(L,I-1)*DXB(I-1))/	B0630
1(2.0*DT)	B0640
RB1(1,I)=(1.0)/((DXB(I-1)/(2.0*XKB(L,I-1)))+(DXB(I-1)/(2.0*XKB(L-1	B0650
1,I-1)))	B0660
RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I)))	B0670
AB(1,I)=RB1(1,I)	B0680
BB(1,I)=(-(RB1(1,I)+RB2(1,I)+SB(1,I)))	B0690
CB(1,I)=RB2(1,I)	B0700
DB(1,I)=(-(SB(1,I)*TX2T(1,I)))	B0710
GO TO 65	B0720
45 IF(FTEST(I)) 50,40,55	B0730
50 G=(1.73E-09)/(1.0/EMBB(I-1)+1.0/EMFB(I)-1.0)	B0740
GO TO 60	B0750
55 G=0.0	B0760
60 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I))/(2.0*DT)	B0770
RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I)))	B0780
AB(1,I)=H(I-1)+4.0*G*(TX2T(L,I-1)**3)	B0790
BB(1,I)=(-(H(I-1)+4.0*G*(TX2T(1,I)**3)+RB2(1,I)+SB(1,I)))	B0800
CB(1,I)=RB2(1,I)	B0810
DB(1,I)=3.0*G*((TX2T(L,I-1)**4)-(TX2T(1,I)**4))-SB(1,I)*TX2T(1,I)	B0820
65 LF=NPM(I)-1	B0830
DO 100 J=2,LF	B0840
SB(J,I)=(RHOBX(I)*CPB(J,I)*DXB(I))/DT	B0850
RB1(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J-1,I)))+(DXB(I)/(2.0*XKB(J,I)))	B0860
RB2(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J+1,I)))+(DXB(I)/(2.0*XKB(J,I)))	B0870
AB(J,I)=RB1(J,I)	B0880
BB(J,I)=(-(RB1(J,I)+RB2(J,I)+SB(J,I)))	B0890
CB(J,I)=RB2(J,I)	B0900
DB(J,I)=(-(SB(J,I)*TX2T(J,I)))	B0910
100 CONTINUE	B0920
IF(I-NMB) 110,250,250	B0930
110 LNF=NPM(I)	B0940
IF(BTEST(I)) 120,115,120	B0950
115 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I)+RHOBX(I+1)*CPB(1,I+1)*DXB(I+1	B0960
1))/2.0*DT)	B0970
RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF	B0980
1,I)))	B0990
RB2(LNF,I)=(1.0)/((DXB(I+1)/(2.0*XKB(1,I+1)))+(DXB(I+1)/	B1000
1(2.0*XKB(2,I+1)))	B1010
AB(LNF,I)=RB1(LNF,I)	B1020
BB(LNF,I)=(-(RB1(LNF,I)+H(I)+SB(LNF,I)+4.0*G*(TX2T(LNF,I)**3)))	B1030
CB(LNF,I)=RB2(LNF,I)	B1040
DB(LNF,I)=(-(SB(LNF,I)*TX2T(LNF,I)))	B1050
GO TO 200	B1060
120 IF(BTEST(I)) 125,115,127	B1070
125 G=(1.73E-09)/(1.0/EMBB(I)+1.0/EMFB(I+1)-1.0)	B1080
GO TO 130	B1090
127 G=0.0	B1100
130 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I))/(2.0*DT)	B1110
RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF	B1120
1,I)))	B1130
AB(LNF,I)=RB1(LNF,I)	B1140
BB(LNF,I)=(-(RB1(LNF,I)+H(I)+SB(LNF,I)+4.0*G*(TX2T(LNF,I)**3)))	B1150
CB(LNF,I)=H(I)+4.0*G*(TX2T(1,I+1)**3)	B1160
DB(LNF,I)=3.0*G*((TX2T(1,I+1)**4)-(TX2T(LNF,I)**4))-SB(LNF,I)*TX2T	B1170
1(LNF,I)	B1180
200 CONTINUE	B1190

250	MN=NPM(NMB)	B1200
	IF(QLOSS) 270,260,270	B1210
260	SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT)	B1220
	RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.0*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*XK	B1230
	1B(MN,NMB)))	B1240
	AB(MN,NMB)=RB1(MN,NMB)	B1250
	BB(MN,NMB)=(-(RB1(MN,NMB)+SB(MN,NMB)))	B1260
	CB(MN,NMB)=0.0	B1270
	DB(MN,NMB)=(-(SB(MN,NMB)*TX2T(MN,NMB)))	B1280
	GO TO 280	B1290
270	SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT)	B1300
	RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.0*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*X	B1310
	1KB(MN,NMB)))	B1320
	AB(MN,NMB)=RB1(MN,NMB)	B1330
	BB(MN,NMB)=(-(RB1(MN,NMB)+HENV+(1.73E-09)*FENV*4.0*(TX2T(MN,NMB)**	B1340
	13)+SB(MN,NMB)))	B1350
	CB(MN,NMB)=0.0	B1360
	DB(MN,NMB)=(-(HENV*TENV+FENV*(1.73E-09)*((TENV**4)+3.0*(TX2T(MN,NM	B1370
	1B)**4))+SB(MN,NMB)*TX2T(MN,NMB)))	B1380
280	L=NP+1	B1390
	DO 300 I=1,NMB	B1400
	K=NPM(I)	B1410
	IF(I.EQ.1) GO TO 282	B1420
	IF(GAPX(I-1).EQ.0.) GO TO 282	B1430
	KT=1	B1440
	GO TO 285	B1450
282	KT=2	B1460
285	DO 290 J=KT,K	B1470
	A(L)=AB(J,I)	B1480
	B(L)=BB(J,I)	B1490
	C(L)=CB(J,I)	B1500
	D(L)=DB(J,I)	B1510
	IF(DMP) 289,289,286	B1520
286	WRITE(6,287) AB(J,I),BB(J,I),CB(J,I),DB(J,I),J,I,A(L),B(L),C(L),D(B1530
	1L),L	B1540
287	FORMAT(1H0,8HAB(J,I)=,1PE12.5,2X,8HBB(J,I)=,1PE12.5,2X,8HCB(J,I)=,	B1550
	11PE12.5,2X,8HDB(J,I)=,1PE12.5,2X,2HJ=,I3,2X,2HI=,I3/1X,5HA(L)=,1PE	B1560
	212.5,2X,5HBL)=,1PE12.5,2X,5HCL)=,1PE12.5,2X,5HDL)=,1PE12.5,2X,2	B1570
	3HL=,I3)	B1580
289	L=L+1	B1590
290	CONTINUE	B1600
300	CONTINUE	B1610
	NPFT=L-1	B1620
	RETURN	B1630
	END	B1640

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$IBFTC PRP                                C0000
C    THIS SUBROUTINE DETERMINES THE PHYSICAL PROPERTIES OF THE C0010
C    HEAT SHIELD STRUCTURE C0020
C    SUBROUTINE PROP C0030
C C0040
C    DIMENSION TITLE(12),HEADING(12),XTDNT(12,12),TKC(20),XKC(20), C0050
C    1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300), C0060
C    2ORAD(300),VEL(300),XNPM(12),NKP(12),NCP(12),TXK(20,12),XK(20,12) C0070
C    3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFR(12),EMBR(12),HXX(12) C0080
C    4,GAPX(12),FTFST(12),RTEST(12),TEMPI(200),TX1(200),TX2(200), C0090
C    5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50), C0100
C    6IR2(50),TUL(50),IEM(50),TY(200),A(200),R(200),C(200),D(200), C0110
C    7R(50),RHO(50),CP(50),DXP(12),XKR(10,12),CPB(10,12),XMDG(50), C0120
C    8YK(50),AB(10,12),RB(10,12),CR(10,12),DB(10,12),SR(10,12), C0130
C    9RR1(10,12),RR2(10,12),H(12),S(50),NPM(12) C0140
C    DIMENSION TT(L(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20) C0150
C C0160
C    COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOX,XPM,FMFR, C0170
C    1FMFR,NKP,NCP,TXK,XK,TCP,CPX,NPM,GAPX,FTFST,RTEST,TEMPI,TX1, C0180
C    2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AR,AB,CR,DB,SR, C0190
C    3RR1,RR2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKR,CPB,DXR,DT,XLOST, C0200
C    4TABL,TCHAR,TREC,RHOV,RHOC,FLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV, C0210
C    5NP,NMR,NPRS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT C0220
C    COMMON I1,I2,I3,I4,I5,I6,QIN,TNT,DX,XMT,TL,VL,BL,NMP,FRR1,ERR2, C0230
C    1FRR3,FRR4,HV,VPT,CHARK,CHARC,ABLK,ARLC,XMDC,H C0240
C C0250
C    KINT=INT C0260
C    DO 170 I=KINT,NP C0270
C    10 IF(IR(I)) 12,12,100 C0280
C    12 TUL(I)=AMAX1(TX1(I),TX2(I)) C0290
C    IF(TUL(I).LE.TABL) GO TO 20 C0300
C    IR(I)=1 C0310
C    GO TO 100 C0320
C    20 IF(I1-1 25,2,21 C0330
C    21 IF(I1-NKV) 22,22,25 C0340
C    22 IF(TX2(I)-TKV(I1)) 35,55,30 C0350
C    25 WRITE(6,26) TX2(I) C0360
C    26 FORMAT(1H0,87H THE RANGE OF ONE OF THE ABLATION PROPERTY CURVE FIT C0370
C    1S WAS EXCEEDED AT A TEMPERATURE OF ,1PE12.5) C0380
C    FRR2=1.0 C0390
C    GO TO 355 C0400
C    30 I1=I1+1 C0410
C    GO TO 21 C0420
C    35 IF(TX2(I)-TKV(I1-1)) 40,55,50 C0430
C    40 I1=I1-1 C0440
C    GO TO 20 C0450
C    50 YK(I)=XKV(I1-1)+((XKV(I1)-XKV(I1-1))/(TKV(I1)-TKV(I1-1))) C0460
C    1*(TX2(I)-TKV(I1-1)) C0470
C    GO TO 60 C0480
C    55 YK(I)=XKV(I1) C0490
C    60 IF(I2-1) 25,25,61 C0500
C    61 IF(I2-NCPV) 62,62,25 C0510
C    62 IF(TX2(I)-TCPV(I2)) 70,85,65 C0520
C    65 I2=I2+1 C0530
C    GO TO 61 C0540
C    70 IF(TX2(I)-TCPV(I2-1)) 75,85,80 C0550
C    75 I2=I2-1 C0560

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GO TO 60	C0570
80 CP(I)=CPV(I2-1)+((CPV(I2)-CPV(I2-1))/(TCPV(I2)-TCPV(I2-1)))	C0580
1*(TX2(I)-TCPV(I2-1))	C0590
GO TO 90	C0600
85 CP(I)=CPV(I2)	C0610
90 RHO(I)=RH0V	C0620
GO TO 170	C0630
100 TUL(I)=AMAX1(TUL(I),TX2(I))	C0640
TF(TUL(I)-TCHAR) 110,110,115	C0650
110 RHO(I)=RH0V+(RH0V-RH0C)*((TUL(I)-TABL)/(TABL-TCHAR))	C0660
YK(I)=CHARK+(ABLK-CHARK)*((RHO(I)-RH0C)/(RH0V-RH0C))	C0670
CP(I)=CHARC+(ABLC-CHARC)*((RHO(I)-RH0C)/(RH0V-RH0C))	C0680
GO TO 170	C0690
115 TF(VPT) 116,116,117	C0700
116 TTUL(I)=TUL(I)	C0710
GO TO 120	C0720
117 TTUL(I)=TX2(I)	C0730
120 TF(I3-1) 25,25,121	C0740
121 TF(I3-NKC) 122,122,25	C0750
122 TF(TTUL(I)-TKC(I3)) 124,135,123	C0760
123 I3=I3+1	C0770
GO TO 121	C0780
124 TF(TTUL(I)-TKC(I3-1)) 125,135,130	C0790
125 I3=I3-1	C0800
GO TO 120	C0810
130 YK(I)=XKC(I3-1)+((XKC(I3)-XKC(I3-1))/(TKC(I3)-TKC(I3-1)))	C0820
1*(TTUL(I)-TKC(I3-1))	C0830
GO TO 140	C0840
135 YK(I)=XKC(I3)	C0850
140 TF(I4-1) 25,25,141	C0860
141 TF(I4-NPC) 142,142,25	C0870
142 TF(TTUL(I)-TCP(I4)) 150,165,145	C0880
145 I4=I4+1	C0890
GO TO 141	C0900
150 TF(TTUL(I)-TCP(I4-1)) 155,165,160	C0910
155 I4=I4-1	C0920
GO TO 140	C0930
160 CP(I)=CPC(I4-1)+((CPC(I4)-CPC(I4-1))/(TCP(I4)-TCP(I4-1)))	C0940
1*(TTUL(I)-TCP(I4-1))	C0950
GO TO 166	C0960
165 CP(I)=CPC(I4)	C0970
166 RHO(I)=RH0C	C0980
170 CONTINUE	C0990
C	C1000
C DETERMINATION OF PROPER BACK-UP SHIELD MATERIAL PROPERTY	C1010
C	C1020
DO 300 I=1,NM	C1030
DXB(I)=XBM(I)/((XNPM(I)-1.0)*12.0)	C1040
LKP=NKPB(I)	C1050
LCP=NCPB(I)	C1060
NN=NPM(I)	C1070
DO 280 J=1,NN	C1080
200 TF(I5-1) 203,203,201	C1090
201 TF(I5-LKP) 202,202,203	C1100
202 TF(TX2T(J,I)-TXK(I5,I)) 206,220,205	C1110
203 WRITE(6,204) I,TX2T(J,I)	C1120
204 FORMAT(1H0,32H THE RANGE OF ONE OF THE NUMBER ,I2,71H BACKUP STRIC	C1130

1	THRE PROPERTY CURVE FITS WAS EXCEEDED AT A TEMPERATURE OF ,1PF12.5	C1140
2)		C1150
	FRR2=1.0	C1160
	GO TO 355	C1170
205	I5=I5+1	C1180
	GO TO 201	C1190
206	IF(TX2T(J,I)-TXK(I5-1,I)) 210,220,215	C1200
210	I5=I5-1	C1210
	GO TO 200	C1220
215	XKB(J,I)=XK(I5-1,I)+((XK(I5,I)-XK(I5-1,I))/(TXK(I5,I)-TXK(I5-1,I))	C1230
	1)*(TX2T(J,I)-TXK(I5-1,I))	C1240
	GO TO 230	C1250
220	XKB(J,I)=XK(I5,I)	C1260
230	IF(I6-1) 203,203,231	C1270
231	IF(I6-LCP) 232,232,203	C1280
232	IF(TX2T(J,I)-TCP(I6,I)) 234,245,233	C1290
233	I6=I6+1	C1300
	GO TO 231	C1310
234	IF(TX2T(J,I)-TCP(I6-1,I)) 235,245,240	C1320
235	I6=I6-1	C1330
	GO TO 230	C1340
240	CPB(J,I)=CPX(I6-1,I)+((CPX(I6,I)-CPX(I6-1,I))/(TCP(I6,I)-TCP(I6-1,	C1350
	I1)))*(TX2T(J,I)-TCP(I6-1,I))	C1360
	GO TO 280	C1370
245	CPB(J,I)=CPX(I6,I)	C1380
280	CONTINUE	C1390
	I5=2	C1400
	I6=2	C1410
300	CONTINUE	C1420
310	IF(DMP) 355,355,320	C1430
320	WRITE(6,330)	C1440
330	FORMAT(/1X,32H PROPERTIES OF ABLATION MATERIAL/)	C1450
	WRITE(6,335)	C1460
335	FORMAT(/5X,5HYK(I),9X,5HCP(I),9X,6HRHO(I)/)	C1470
	WRITE(6,340) (YK(I),CP(I),RHO(I),I=1,NP)	C1480
340	FORMAT(2X,1PF12.5,2X,1PF12.5,2X,1PE12.5)	C1490
	WRITE(6,345)	C1500
345	FORMAT(/1X,32H PROPERTIES OF BACK-UP STRUCTURE/)	C1510
	WRITE(6,347)	C1520
347	FORMAT(/5X,8HYKR(J,I),7X,8HCPB(J,I),7X,8HRHOBX(I),7X,7HFMBB(I),8X,	C1530
	17HEMBR(I),9X,6HDXB(I)/)	C1540
	DO 350 I=1,NMR	C1550
	KL=NPM(I)	C1560
	DO 349 J=1,KL	C1570
	WRITE(6,348) YKR(J,I),CPB(J,I),RHOBX(I),FMBB(I),FMBR(I),DXB(I)	C1580
348	FORMAT(3X,1PF12.5,3X,1PE12.5,3X,1PE12.5,3X,1PF12.5,3X,1PF12.5,3X,1	C1590
	1PF12.5)	C1600
349	CONTINUE	C1610
350	CONTINUE	C1620
355	RETURN	C1630
	END	C1640

\$IBFTC ABL	n0000
C THIS SUBROUTINE DETERMINES THE MASS FLOW RATE FROM THE	n0010
C ABLATING NODES	n0020
C SUBROUTINE ABLATE	n0030
C	n0040
DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),	n0050
1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),	n0060
20PAD(300),VEL(300),XNPM(12),NKPR(12),NCPB(12),TXK(20,12),XK(20,12)	n0070
3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFB(12),EMBR(12),HXX(12)	n0080
4,GAPX(12),FTFST(12),RTEST(12),TEMPI(200),TX1(200),TX2(200),	n0090
5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),	n0100
6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),	n0110
7R(50),RHO(50),CP(50),DXP(12),XKB(10,12),CPB(10,12),XMDG(50),	n0120
8YK(50),AB(10,12),RB(10,12),CB(10,12),DB(10,12),SR(10,12),	n0130
9RRI(10,12),RRI2(10,12),H(12),S(50),NPM(12)	n0140
DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)	n0150
C	n0160
COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XRM,FMFB,	n0170
1FMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTFST,RTEST,TEMPI,TX1,	n0180
2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,RB,CB,DB,SR,	n0190
3RRI,RRI2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXR,DT,XLOST,	n0200
4TABL,TCHAR,TRFC,RHOV,RHOC,FLOW,FMV,EMC,H300,NKC,NCPB,NKV,NCPV,	n0210
5NP,NMR,NPRS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FFNV,QLOSS,TLIM,TINT	n0220
COMMON I1,I2,T3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,FRR1,ERR2,	n0230
1FRR3,FRR4,HV,VPT,CHARK,CHARC,ABLK,ARLC,XMDC,H	n0240
C	n0250
XMT=0.0	n0260
LINT=INT	n0270
KI=NP	n0280
IF(DMP) 8,8,3	n0290
3 WRITE(6,5)	n0300
5 FORMAT(//1X,20HMASS FLOW FROM ABLATING NODES//)	n0310
8 DO 200 KKI=LINT,NP	n0320
IF(IR1(KKI)) 11,11,12	n0330
11 IF(TX1(KKI).LE.TABL) GO TO 9	n0340
12 TUL1(KKI)=AMAX1(TUL1(KKI),TX1(KKI))	n0350
TPI(KKI)=1	n0360
GO TO 20	n0370
9 IF(TX1(KKI)-TABL) 10,10,20	n0380
10 RHOY1(KKI)=RHOV	n0390
GO TO 50	n0400
20 IF(TUL1(KKI)-TCHAR) 40,30,30	n0410
30 RHOY1(KKI)=RHOC	n0420
GO TO 50	n0430
40 RHOY1(KKI)=RHOV+(RHOV-RHOC)*((TUL1(KKI)-TARI)/(TARI-TCHAR))	n0440
50 IF(IR2(KKI)) 52,52,54	n0450
52 IF(TX2(KKI).LE.TABL) GO TO 56	n0460
54 TUL2(KKI)=AMAX1(TUL2(KKI),TX2(KKI))	n0470
IR2(KKI)=1	n0480
GO TO 70	n0490
56 IF(TX2(KKI)-TABL) 60,60,70	n0500
60 RHOY2(KKI)=RHOV	n0510
GO TO 95	n0520
70 IF(TUL2(KKI)-TCHAR) 90,80,80	n0530
80 RHOY2(KKI)=RHOC	n0540
GO TO 95	n0550
90 RHOY2(KKI)=RHOV+(RHOV-RHOC)*((TUL2(KKI)-TABL)/(TABL-TCHAR))	n0560

95	DRHO(KI)=((RHOY1(KI)-RHOY2(KI))/DT)*DX	00570
	IF(KI-NP) 97,96,96	00580
96	DRHO(KI)=DRHO(KI)/2.0	00590
	GO TO 98	00600
97	IF(KI-INT) 96,96,98	00610
98	IF(DRHO(KI)) 110,120,120	00620
110	DRHO(KI)=0.0	00630
120	XMT=XMT+DRHO(KI)	00640
	XMDG(KI)=XMT	00650
	IF(DMP) 190,190,150	00660
150	WRITE(6,160) XMDG(KI),DRHO(KI),RHOY2(KI),RHOY1(KI)	00670
160	FORMAT(1X,5HXMDG=,1PE12.5,2X,5HDRHO=,1PF12.5,2X,6HRRHOY2=,1PE12.5,2	00680
	1X,6HRRHOY1=,1PF12.5)	00690
190	KI=KI-1	00700
200	CONTINUE	00710
	RETURN	00720
	END	00730

\$IBFTC OXID	F0000
C	F0010
C THIS SUBROUTINE CALCULATES THE HEATING RATE DUE TO COMBUSTION	F0020
C IT IS ASSUMED THAT OXYGEN AND CARBON REACT TO FORM CO ONLY.	F0030
C	F0040
C SUBROUTINE OXIDAT(XMDO,GOXID)	F0050
C	F0060
GOXID=XMDO*4000.0/3600.0	F0070
GOXID=0.0	F0080
RETURN	F0090
END	F0100

\$IBFTC SWUFT	F0000
C THIS SUBROUTINE DETERMINES THE FORWARD TIME STEP TEMPERATURES	F0010
C BY SOLVING THE TRI-DIAGONAL MATRIX	F0020
SUBROUTINE SWUFT(A,B,C,D,T,N,DMP)	F0030
DIMENSION A(200),B(200),C(200),D(200),T(200),CP(200),DP(200)	F0040
CP(1)=C(1)/B(1)	F0050
DP(1)=D(1)/B(1)	F0060
DO 100 I=2,N	F0070
CP(I)=(C(I)-(B(I)-A(I)*CP(I-1))	F0080
DP(I)=(D(I)-A(I)*DP(I-1))/(B(I)-A(I)*CP(I-1))	F0090
100 CONTINUE	F0100
T(N)=DP(N)	F0110
NM1=N-1	F0120
DO 200 J=1,NM1	F0130
I=N-J	F0140
T(I)=DP(I)-CP(I)*T(I+1)	F0150
200 CONTINUE	F0160
IF(DMP) 300,300,250	F0170
250 WRITE(6,260)	F0180
260 FORMAT(/,1X,4*HCoefficients calculated by SUBROUTINE SWUFT//)	F0190
WRITE(6,270)	F0200
270 FORMAT(6X,5HCP(I),10X,5HDP(I),10X,4HT(I)/)	F0210
WRITE(6,275) (CP(I),DP(I),T(I),I=1,N)	F0220
275 FORMAT(2X,1PE12.5,2X,1PE12.5,2X,1PE12.5)	F0230
300 RETURN	F0240
END	F0250

\$IBFTC REC	60000
C	60010
C THIS SUBROUTINE DETERMINES THE FRONT FACE LOCATION AND CHAR MASS	60020
C REMOVAL RATE	60030
C	60040
SUBROUTINE RFCESS(XMDC,XLOST,TRFC,DT,RHOC,TS,SR,TX2,NREC,NRS,FRR5,	60050
1SX0,SDOT,DMP)	60060
C	60070
DIMENSION TS(50),SR(50)	60080
IF(TX2-TRFC) 10,20,20	60090
10 XMDC=0.0	60100
XLOST=0.0	60110
SDOT=0.0	60120
GO TO 60	60130
20 IF(NRS-1)25,25,21	60140
21 IF(NRS-NREC) 22,22,25	60150
22 IF(TX2-TS(NRS)) 32,40,30	60160
25 WRITE(6,26) TX2	60170
26 FORMAT(1H0,75H THE RANGE OF THE SURFACE RFCESSION TABLE WAS EXCEED	60180
1ED AT A TEMPERATURE OF ,1PE12.5)	60190
FRR5=1.0	60200
GO TO 60	60210
30 NRS=NRS+1	60220
GO TO 21	60230
32 IF(TX2-TS(NRS-1)) 34,40,36	60240
34 NRS=NRS-1	60250
GO TO 20	60260
36 SX=SR(NRS-1)+((SR(NRS)-SR(NRS-1))/(TS(NRS)-TS(NRS-1)))	60270
1*(TX2-TS(NRS-1))	60280
GO TO 50	60290
40 SX=SR(NRS)	60300
50 XLOST=300.0*SX*DT	60310
XMDC=(XLOST*RHOC)/DT	60320
SDOT=SX*300.0	60330
IF(DMP) 60,60,52	60340
52 WRITE(6,54) SX,XLOST,XMDC	60350
54 FORMAT(1H0,3HSX=,1PE12.5,3X,6HXLOST=,1PE12.5,3X,5HXMDC=,1PE12.5)	60360
60 RETURN	60370
END	60380

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SIBFTC TEMP                                H0000
C      THIS SUBROUTINE DETERMINES THE INITIAL TEMPERATURE DISTRIBUTION          H0010
C      IN THE HEAT SHIELD STRUCTURE                                           H0020
C      SUBROUTINE TEMPD                                                         H0030
C                                                                              H0040
C      DIMENSION TITLE(12),HEADING(12),XIDNT(12,12),TKC(20),XKC(20),          H0050
1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),              H0060
2ORAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)         H0070
3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBR(12),HXX(12)         H0080
4,GAPX(12),FTEST(12),RTEST(12),TEMPI(200),TX1(200),TX2(200),              H0090
5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),            H0100
6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),              H0110
7R(50),RHO(50),CP(50),DXR(12),XKR(10,12),CPB(10,12),XMDG(50),              H0120
8YK(50),AB(10,12),RB(10,12),CR(10,12),DB(10,12),SB(10,12),                H0130
9RR1(10,12),RR2(10,12),H(12),S(50),NPM(12)                                  H0140
C      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)              H0150
C                                                                              H0160
C      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XRM,EMBB,          H0170
1FMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,RTEST,TEMPI,TX1,              H0180
2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CR,DB,SB,              H0190
3RR1,RR2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKR,CPB,DXR,DT,XLOST,                H0200
4TABL,TCHAR,TRFC,RHOV,RHOC,FLOW,FMV,EMC,H300,NKC,NPC, NKV,NCPV,              H0210
5NP,NMR,NPRS,NPF,TST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT              H0220
COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,FRR1,ERR2,              H0230
1FRR3,FRR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H                             H0240
C                                                                              H0250
C      X=0.0                                                                    H0260
TF(TEST2) 300,100,200                                                         H0270
100 DO 150 L=1,NPF                                                             H0280
TX1(L)=TEMPI                                                                    H0290
TX2(L)=TEMPI                                                                    H0300
TUL1(L)=TX1(L)                                                                  H0310
TUL2(L)=TX2(L)                                                                  H0320
TEMPI(L)=TEMPI                                                                  H0330
150 CONTINUE                                                                    H0340
DO 160 I=1,NMR                                                                  H0350
JN=NPM(I)                                                                        H0360
DO 155 M=1,JN                                                                    H0370
TX2T(M,I)=TEMPI                                                                H0380
155 CONTINUE                                                                    H0390
160 CONTINUE                                                                    H0400
GO TO 320                                                                        H0410
200 DO 220 L=1,NP                                                                H0420
TEMPI(L)=TX0+((TENV-TX0)/TL)**X                                                H0430
TX1(L)=TEMPI(L)                                                                H0440
TX2(L)=TX1(L)                                                                  H0450
TUL1(L)=TX1(L)                                                                  H0460
TUL2(L)=TX1(L)                                                                  H0470
X=X+DX                                                                            H0480
220 CONTINUE                                                                    H0490
L=NP+1                                                                            H0500
DO 270 I=1,NMR                                                                  H0510
KJ=NPM(I)                                                                        H0520
DO 250 J=1,KJ                                                                    H0530
TEMPI(L)=TX0+((TENV-TX0)/TL)**X                                                H0540
TX1(L)=TEMPI(L)                                                                H0550
TX2(L)=TEMPI(L)                                                                H0560

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	TX2T(J,I)=TEMPI(L)	H0570
	X=X+DXB(I)	H0580
	L=L+1	H0590
250	CONTINUE	H0600
	X=X+(GAPX(I)/12.0)	H0610
270	CONTINUE	H0620
	GO TO 320	H0630
C	AN ARBITRARY TEMPERATURE DISTRIBUTION CAN BE READ IN FROM INPUT	H0640
C	DATA IF TEST2 IS A NEGATIVE NUMBER	H0650
300	WRITE(6,310)	H0660
310	FORMAT(1H0,79H THE VALUE OF TEST2 WAS NEGATIVE, SUBROUTINE TEMPD S	H0670
	HOULD NOT HAVE BEEN CALLED.)	H0680
	FRR1=1.0	H0690
320	RETURN	H0700
	END	H0710

SIBFTC DON2	10000
C THIS SUBROUTINE DETERMINES THE TEMPERATURE OF POINTS A FIXED	10010
C DISTANCE FROM A REFERENCE PLANE FROM THE TEMPERATURES CALCULATED	10020
C IN A VARYING THICKNESS	10030
C	10040
SUBROUTINE DON2(XLSTV,XARRAY,TARRAY,NA,XNODE,TEMP,XNODEV,KK,XLSTV,	10050
1DX)	10060
C	10070
DIMENSION XARRAY(50),TARRAY(50),XNODE(50),TEMP(50),XNODEV(50)	10080
C	10090
K=0	10100
DXT=0.0	10110
DO 100 I=1,NA	10120
IF(XLSTV.LE.DXT) GO TO 150	10130
K=K+1	10140
100 DXT=DXT+DX	10150
150 KK=NA-K	10160
XK=K	10170
XNODEV(1)=XLSTV	10180
TFMP(1)=TARRAY(1)	10190
DO 200 I=1,KK	10200
XNODE(I)=XK*DX-XLSTV	10210
CALL DISCT3(XNODE(I),XARRAY,TARRAY,NA,TFMP(I+1))	10220
XNODEV(I+1)=XK*DX	10230
200 XK=XK+1.0	10240
RETURN	10250
END	10260

SIBFIC UINTRP	J00000
SUBROUTINE UINTRP(X,XTBL,Y,YTBL,N,J)	J00010
DIMENSION XTBL(50),YTBL(50)	J00020
I=J	J00030
IF(I.GT.N.OR.Y.LT.2) I=2	J00040
10 IF(XTBL(I-1).LE.X.AND.X.LE.YTBL(I)) GO TO 40	J00050
IF(X.GT.XTBL(I)) GO TO 30	J00060
20 I=I-1	J00070
IF(I.GE.2) GO TO 10	J00080
I=2	J00090
GO TO 40	J01000
30 I=I+1	J01100
IF(I.LE.N) GO TO 10	J01200
I=N	J01300
40 FRACT=(X-XTBL(I-1))/(XTBL(I)-XTBL(I-1))	J01400
Y=YTBL(I-1)+(YTBL(I)-YTBL(I-1))*FRACT	J01500
RETURN	J01600
END	J01700

\$IBFTC ISOT	K0000
SUBROUTINE ISOTHM(DEPTH,TEMP,ROND,N,ANS)	K0010
DIMENSION DEPTH(1),TEMP(1)	K0020
ANS=-1.	K0030
K=N-1	K0040
DO 100 I=1,K	K0050
IF(TEMP(I)-BOND)2,1,3	K0060
1 ANS=DEPTH(I)	K0070
GO TO 100	K0080
2 IF(TEMP(I+1)-ROND)100,100,4	K0090
4 ANS=DEPTH(I+1)-(TEMP(I+1)-BOND)*(DEPTH(I+1)-DEPTH(I))/(TEMP(I+1)-	K0100
TEMP(I))	K0110
GO TO 100	K0120
3 IF(TEMP(I+1)-ROND)5,100,100	K0130
5 ANS=(TEMP(I)-ROND)*(DEPTH(I+1)-DEPTH(I))/(TEMP(I)-TEMP(I+1))+DEPTH	K0140
1(I)	K0150
100 CONTINUE	K0160
IF(ROND.EQ.TEMP(N))ANS=DEPTH(N)	K0170
RETURN	K0180
END	K0190

\$IBFTC SAVE	L0000
SUBROUTINE SAVE(SAVE1,SAVF2,SAVF3,USE,NX1,VALUE,DT,TFINAL,TIME,	L0010
1THING)	L0020
DIMENSION SAVF1(1),SAVE2(1),SAVE3(1)	L0030
USE=0.0	L0040
SAVE1(NX1)=VALUE	L0050
NX2=NX1-1	L0060
IF(NX2.EQ.0)NX2=3	L0070
SAVF2(NX2)=VALUE	L0080
NX3=NX2-1	L0090
IF(NX3.EQ.0)NX3=3	L0100
SAVF3(NX3)=VALUE	L0110
IF((TIME.LT.(2.*DT)).OR.(TIME.GT.(TFINAL-3.*DT)))GO TO 4	L0120
GO TO (1,2,3),NX1	L0130
1 IF(((ABS(SAVF2(1)-SAVF2(2))).LE..001).OR.(ABS(SAVE2(2)-SAVE2(3))	L0140
1.LE..001))GO TO 5	L0150
IF(((SAVE2(1).LT.SAVF2(2)).AND.(SAVE2(2).GT.SAVF2(3))).OR.((SAVF2(L0160
11).GT.SAVF2(2)).AND.(SAVF2(2).LT.SAVE2(3))))USE=SAVE2(2)	L0170
5 THING=SAVF2(2)	L0180
GO TO 4	L0190
2 IF(((ABS(SAVE3(1)-SAVF3(2))).LE..001).OR.(ABS(SAVE3(2)-SAVE3(3))	L0200
1.LE..001))GO TO 6	L0210
IF(((SAVE3(1).LT.SAVF3(2)).AND.(SAVE3(2).GT.SAVF3(3))).OR.((SAVF3(L0220
11).GT.SAVF3(2)).AND.(SAVF3(2).LT.SAVE3(3))))USE=SAVF3(2)	L0230
6 THING=SAVF3(2)	L0240
GO TO 4	L0250
3 IF(((ABS(SAVE1(1)-SAVF1(2))).LE..001).OR.(ABS(SAVF1(2)-SAVE1(3))	L0260
1.LE..001))GO TO 6	L0270
IF(((SAVE1(1).LT.SAVF1(2)).AND.(SAVE1(2).GT.SAVF1(3))).OR.((SAVF1(L0280
11).GT.SAVF1(2)).AND.(SAVF1(2).LT.SAVE1(3))))USE=SAVF1(2)	L0290
7 THING=SAVF1(2)	L0300
4 NX1=NX1+1	L0310
IF(NX1.EQ.4)NX1=1	L0320
RETURN	L0330
END	L0340

```

$IBFTC DISCT3
SUBROUTINE DISCT3(XA,TABX,TABY,NY,ANS)
  DIMENSION TABX(1),TABY(1)
  CALL DISSFR(XA,TABX,1,NY,2,NN)
  NNN=3
  CALL LAGRAN(XA,TABX(NN),TABY(NN),NNN,ANS)
  RETURN
END

```

```

M0000
M0010
M0020
M0030
M0040
M0050
M0060
M0070

```

\$IBFTC DISS	W0000
SUBROUTINE DISSER (XA,TAB,I,NX,ID,NPX)	W0010
DIMENSION TAB(2000)	W0020
C DIMENSION TAB(2000)	W0030
NPT=ID+1	W0040
NPB=NPT/2	W0050
NPU=NPT-NPB	W0060
IF (NX-NPT) 10,5,10	W0070
5 NPX=I	W0080
RETURN	W0090
10 NLOW=I+NPB	W0100
NUPP=I+NX-(NPU+1)	W0110
DO 15 II=NLOW,NUPP	W0120
NLOC=II	W0130
IF (TAB(II)-XA) 15,20,20	W0140
15 CONTINUE	W0150
NPX=NUPP-NPB+1	W0160
RETURN	W0170
20 NL=NLOC-NPB	W0180
NU=NL+ID	W0190
DO 25 JJ=NL,NU	W0200
NDIS=JJ	W0210
IF (TAB(JJ)-TAB(JJ+1)) 25,30,25	W0220
25 CONTINUE	W0230
NPX=NL	W0240
RETURN	W0250
30 IF (TAB(NDIS)-XA) 40,35,35	W0260
35 NPX=NDIS-ID	W0270
RETURN	W0280
40 NPX=NDIS+1	W0290
RETURN	W0300
END	W0310

```

$IBFTC LAGR
SUBROUTINE LAGRAN (XA,X,Y,N,ANS)
DIMENSION X(200),Y(200)
C DIMENSION X(200),Y(200)
SUM=0.0
DO 3 I=1,N
  PROD=Y(I)
  DO 2 J=1,N
    A=X(I)-X(J)
    IF (A) 1,2,1
1  B=(XA-X(J))/A
  PROD=PROD*B
2 CONTINUE
3 SUM=SUM+PROD
ANS=SUM
RETURN
END

```

```

T0000
T0010
T0020
T0030
T0040
T0050
T0060
T0070
T0080
T0090
T0100
T0110
T0120
T0130
T0140
T0150
T0160

```

SIBFTC MORE	N0000
DIMENSION TITLE(12),X(2000),Y1(2000),Y2(2000),Y3(2000),Y4(2000)	N0010
RFWIND 11	N0020
RFAD(11) (TITLE(I),I=1,12)	N0030
RFAD(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)	N0040
Y3(1)=Y3(1)*12.+Y1(1)	N0050
Y4(1)=Y4(1)*12.+Y1(1)	N0060
I=2	N0070
30 RFAD(11)X(I),Y1(I),Y2(I),Y3(I),Y4(I)	N0080
IF(X(I)-5001.)10,20,20	N0090
10 Y3(I)=Y3(I)*12.+Y1(I)	N0100
Y4(I)=Y4(I)*12.+Y1(I)	N0110
I=I+1	N0120
GO TO 30	N0130
20 NPLOT=I-1	N0140
YM1=Y1(1)	N0150
YM2=Y2(1)	N0160
YM3=Y3(1)	N0170
YM4=Y4(1)	N0180
DO 40 K = 2 , NPLOT	N0190
IF (Y1(K).GT.YM1) YM1 = Y1(K)	N0200
IF (Y2(K).GT.YM2) YM2 = Y2(K)	N0210
IF (Y3(K).GT.YM3) YM3 = Y3(K)	N0220
IF (Y4(K).GT.YM4) YM4 = Y4(K)	N0230
40 CONTINUE	N0240
1000 FORMAT(1H1,(12A6))	N0250
CALL ACCEND(X,Y1,Y2,Y3,Y4,NPLOT)	N0260
XMAX=X(NPLOT)	N0270
CALL APLOT (X,Y1,XMAX,YM1,TITLE,NPLOT)	N0280
CALL RPLOT (X,Y2,XMAX,YM2,TITLE)	N0290
CALL CPLOT (X,Y3,Y4,XMAX,YM3,YM4,TITLE,Y1)	N0300
WRITE(6,1000)(TITLE(I),I=1,12)	N0310
WRITE(6,1001)(X(I),Y1(I),Y2(I),Y3(I),Y4(I),I=1,NPLOT)	N0320
1001 FORMAT(5E20.8)	N0330
WRITE(6,1002)XMAX,YM1,YM2,YM3,YM4,NPLOT	N0340
1002 FORMAT(///6H XMAX=F10.4,5H YM1=F10.4,5H YM2=F10.4,5H YM3=F10.4,5H	N0350
1YM4=F10.4,2X6HNPLOT=I4)	N0360
RFAD(11) (TITLE(I),I = 1,12)	N0370
RFAD(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)	N0380
I=2	N0390
IF(X(1)-5001.)30,50,50	N0400
50 WRITE(6,1003)(TITLE(I),I=1,12)	N0410
1003 FORMAT(///12A6)	N0420
RETURN	N0430
END	N0440

SIBFTC ACCEN	P0000
SUBROUTINE ACCEND(X,Y,A,B,C,N)	P0010
DIMENSION X(1),Y(1),A(1),B(1),C(1)	P0020
K=1	P0030
101 SMALL=X(K)	P0040
DO 100 I=K,N	P0050
DUMY=X(I)	P0060
SMALL=AMIN1(SMALL,DUMY)	P0070
IF(SMALL.EQ.X(I))INDEX=I	P0080
100 CONTINUE	P0090
X(INDEX)=X(K)	P0100
X(K)=SMALL	P0110
SAVE=Y(K)	P0120
Y(K)=Y(INDEX)	P0130
Y(INDEX)=SAVE	P0140
SAVEA=A(K)	P0150
A(K)=A(INDEX)	P0160
A(INDEX)=SAVEA	P0170
SAVEB=B(K)	P0180
B(K)=B(INDEX)	P0190
B(INDEX)=SAVEB	P0200
SAVEC=C(K)	P0210
C(K)=C(INDEX)	P0220
C(INDEX)=SAVEC	P0230
K=K+1	P0240
IF(K.EQ.N)RETURN	P0250
GO TO 101	P0260
END	P0270

\$IBFIC PPLOT	R0000
SUBROUTINE PPLOT (X,Y,XLYM,YLYM,TITLE)	R0010
DIMENSION X(300),Y(300),YTITLE(10),ALONGY(7),YTITLE(10)	R0020
DIMENSION TITLE(12)	R0030
COMMON /ARC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX	R0040
DATA (XTITLE(I),I=1,10)/3AH	R0050
DATA (YTITLE(I),I=1,10)/3AH	R0060
ALONGY(1)=0.0	R0070
DO 10 I=1,7	R0080
TI=I	R0090
IF(YLYM-ALLOW(I)) 20,20,10	R0100
10 CONTINUE	R0110
WRITE (6,1000) YLYM	R0120
1000 FORMAT(/// 37H PPLOT WILL NOT BE DONE BECAUSE YLYM= E12.5 ///)	R0130
RETURN	R0140
20 YMAX =ALLOW(TI)	R0150
CALL RSTERN	R0160
CALL GRIDGN(123,1023,24,924,18,18,5,5)	R0170
CALL PLOT1 (1,1,ZERO,XMAX,ZERO,YMAX,X,Y, NPLOT,1, 1H/)	R0180
DO 30 I=1,6	R0190
CALL LABELX (ALONGX(I),1)	R0200
CALL LABELY (ALONGY(I),1)	R0210
30 ALONGY(I+1) = ALONGY(I) + .2* YMAX	R0220
CALL PRINT(200,975,12,0,38,XTITLE)	R0230
CALL PRINT(47,200,0,12,38,YTITLE)	R0240
CALL PRINT(123,1000,12,0,72,TITLE)	R0250
CALL DMPBUF	R0260
RETURN	R0270
END	R0280

```

$IBFTC C PLOT
SUBROUTINE C PLOT (X,Y1,Y2,XLIM,YLIM1,YLIM2,TITLE, Y)
DIMENSION X(300),Y1(300),Y2(300),YTITLE(10),YY(2000),XTITLE(10)
DIMENSION TITLE(12),Y(300),ALONGY(7)
DIMENSION CURVE(1),VRUG(4),HRUG(7)
COMMON /ARC / ALLOW(7),ALONGX(7),NPLOT,ZFRO,XMAX,IFIX
DATA (VRUG(I),I=1,4) / 100.0,50.0,20.0,10.0 /
DATA (HRUG(I),I=1,7) / 1.0,2.0,5.0,10.0,20.0,50.0,100.0 /
DATA (XTITLE(I),I=1,10)/38H
DATA (YTITLE(I),I=1,10)/38H
DATA ONE/4H1060 /,TWO/4H1460 /
DATA WON/1H1 /,TOO/1H2 /
C *** FOUR (4) CHARACTERS ARE ALLOWED FOR CURVE(1)
CURVE(1)=ONE
HFACTOR=HRUG(IFIX)
SYMBOL=WON
YBIG =AMAX1 (YLIM1,YLIM2 )
NCURVE =1
DO 1 I=1,NPLOT
1 YY(I)= Y1(I)
DO 7 I=1,4
II= I
IF(YBIG*100. -ALLOW(I))6,6,7
7 CONTINUE
WRITE (6,1000) YLIM1,YLIM2
1000 FORMAT (/// 38H (PLOT WILL NOT BE DONE BECAUSE YLIM1=F12.5,10H OR
1YLIM2= F12.5 /// )
RETURN
6 YMAX =ALLOW (II)/100.
VFACIR=VRUG(II)
CALL RSTPRM
CALL GRTUCN (123,1023,24.024,18,18,5,5)
J=1
70 DO 10 I=J,NPLOT
II= I
IM1 =I-1
IF( YY(I)-Y(I) )20,10,10
10 CONTINUE
NOPT=NPLOT-J+1
LI=J + NOPT/2
IVLOC=(YMAX-YY(LL))*18.*VFACIR +24. -4.
IHLOC= X(LL)*18. /HFACTOR +123. -48.
CALL PRINT(IHLOC,IVLOC, 8,0,4,CURVE)
CALL PLOT1(1,1,ZFRO,XMAX,ZFRO,YMAX,X(J),YY(J),NOPT ,1,SYMBOL)
IF (NCURVE=1 ) 90,85,90
85 DO 86 I=1,NPLOT
86 YY(I)=Y2(I)
CURVE(1)=TWO
SYMBOL=TOO
NCURVE = 2
J=1
GO TO 70
20 NPT=IT-J
LI=J + NPT/2
IVLOC=(YMAX-YY(LL))*18.*VFACIR +24. -4.
IHLOC= X(LI)*18. /HFACTOR +123. -48.
CALL PRINT(IHLOC,IVLOC, 8,0,4,CURVE)

```

CALL PL011(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),NPT,1,SYMBOL)	50570
DO 50 IJ= II, NPL0T	50580
JJ= IJ	50590
IF(YY(IJ)- Y(IJ))50,40,40	50600
50 CONTINUE	50610
IF(NCURVE-1) 90,85,90	50620
40 JJ= JJ	50630
GO TO 70	50640
90 ALONGY(1)=0.0	50650
DO 100 I=1,6	50660
CALL LABELX(ALONGX(I), 1)	50670
CALL LABELY(ALONGY(I),1)	50680
100 ALONGY(I+1)=ALONGY(I) + .2*YMAX	50690
CALL PRINT(200,975,12,0,38,XTITLE)	50700
CALL PRINT(47,200,0,12,38,YTITLE)	50710
CALL PRINT(123,1000,12,0,72,TITLE)	50720
CALL DMPBIF	50730
RETURN	50740
END	50750

APPENDIX D

PROGRAM TERMINOLOGY

<u>FORTRAN</u>	<u>Description</u>
A	"A" coefficient in matrix, single subscript
AB	"A" coefficient in matrix, double subscript
ABLC	specific heat of material at TABL
ABLK	thermal conductivity of material at TABL
B	"B" coefficient in matrix, single subscript
BB	"B" coefficient in matrix, double subscript
BL	Total thickness of backup structure
BLTEM	value of 1460 isotherm depth from previous time step
BTEST	test to determine mode of heat transfer out of back surface of backup materials
C	"C" coefficient in matrix, single subscript
CB	"C" coefficient in matrix, double subscript
CHARC	specific heat of material at TCHAR
CHARK	thermal conductivity of material at TCHAR
CP	specific heat of a node in ablation material
CPB	specific heat of backup material node
CPC	specific heat values in char specific heat table
CPV	specific heat values in virgin specific heat table
CPX	specific heat values in backup material specific heat tables
D	"D" coefficient in matrix, single subscript
DB	"D" coefficient in matrix, double subscript
DELTT	time step in the time step table

<u>FORTTRAN</u>	<u>Description</u>
DMP	test used for dumping (DMP = 0 skip dump, DMP = 1.0 start dumping)
DRHØ	local mass flow rate of ablation gas
DT	time step from the time step table in hours
DTS	time step from time step table in seconds
DX	thickness of a node in the ablation material
DXB	thickness of a node in a backup structure material
DXV	variable ablation node thickness $\left(= \frac{VLV}{NP - 1} \right)$
DXX	fixed ablation material node thickness $\left(= \frac{VLI}{NP - 1} \right)$
EMBB	emissivity of back surface of each material in backup
EMC	char material emissivity
EMFB	emissivity of front surface of each material in backup
EMV	virgin material emissivity
EMX	emissivity of front surface of ablation material
END	code word for plot routine
ERR1	Control numbers for printing error statements when an input or calculational mistake is made
ERR2	
ERR3	
ERR4	
FBLØW	blowing efficiency in reducing convective heating
FCØNV	factor to correct convective heating rate for various body locations
FENV	emissivity - view factor product to cabin interior
FRAD	factor to correct radiative heating rate for various body locations
FTEST	test to determine mode of heat transfer into front surface of backup materials

<u>FORTTRAN</u>	<u>Description</u>
FV	view factor for external environment
G	defined by FORTTRAN statement
GAPX	gap width between backup materials
H	film coefficient between backup materials
H300	enthalpy of air at 300° K
HEAD	any 72 alphanumeric characters used to identify problems being run - printed at top of first page of output
HEADNG	any 72 alphanumeric characters used to identify each input section
HENV	film coefficient to cabin environment
HTX	total enthalpy
HV	heat of degradation of virgin material
HW	wall enthalpy computed from enthalpy - temperature table
HX	enthalpy values in enthalpy table
ITEM	test used to determine if front surface is virgin or char for using proper emissivity
IPRC	variable print frequency in time-step table
IPRCT	present print control number
IR	test to determine if node temperature is greater than TABL
IR1	test used in determining node density at TX1 temperature
IR2	test used in determining node density at TX2 temperature
NCASE	number of problems to be run
NCPB	number of points in each backup material specific heat table
NCP C	number of points in char specific heat temperature table
NCPV	number of points in virgin specific heat temperature table
NKC	number of points in char thermal conductivity - temperature table

<u>FORTTRAN</u>	<u>Description</u>
NKPB	number of points in each backup material thermal conductivity table
NKV	number of points in virgin thermal conductivity temperature table
NMB	number of materials in backup structure
NP	number of node points in ablation material
NPBS	total number of node points in backup structure
NPF	total number of points in heat shield structure (NP + NPBS)
NPLØT	output plot control number
NPM	number of nodes per material in backup
NHP	number of points in enthalpy - temperature table
NPTT	number of points in time-step table
NREC	number of points in surface recession - temperature or time table
NTRAPT	number of points in trajectory input table
NXA	} dummy indices for subroutine SAVE
NXB	
NXC	
NXD	
NXE	
QBLØCK	amount of convective heat blocked due to mass injection into boundary layer
QCØN	trajectory table convective heating rates
QCØNX	cold wall convective heat rate at present time step
QHW	hot wall convective heat rate without blowing
QIN	net heat flux into front surface
QLØSS	boundary condition for heat transfer to cabin interior
QØXID	heating rate due to combustion

<u>FORTTRAN</u>	<u>Description</u>
QRAD	trajectory table radiative heating rates
QRADX	radiative heat flux at present time step
QUIT	code word for plot routine
R	thermal resistance due to conductivity between nodes in the ablation material
RB1	thermal resistance due to conductivity between past and present node in backup material
RB2	thermal resistance due to conductivity between present and forward node in backup material
RHØ	density of an ablation material node
RHØBX	density of individual materials in backup
RHØC	mature char material density
RHØV	virgin ablation material density
RHØY1	density of node at past time step
RHØY2	density of node at present time step
S	thermal capacity of a node in the ablation material
SDØT	surface recession rate
SAVEIT	depth of 1060 isotherm at any given time
SAVEXX	time corresponding to maximum depth of 1460 isotherm
SAVX	time corresponding to maximum depth of 1060 isotherm
SAVY1	surface recession depth at maximum 1060 isotherm depth
SAVY2	bondline temperature at maximum 1060 isotherm depth
SAVY3	term that will contain maximum depth of 1060 isotherm
SAVY4	depth of 1460 isotherm at maximum 1060 isotherm depth
SAVY1X	surface recession depth at maximum 1460 isotherm depth
SAVY2X	bondline temperature at maximum 1460 isotherm depth

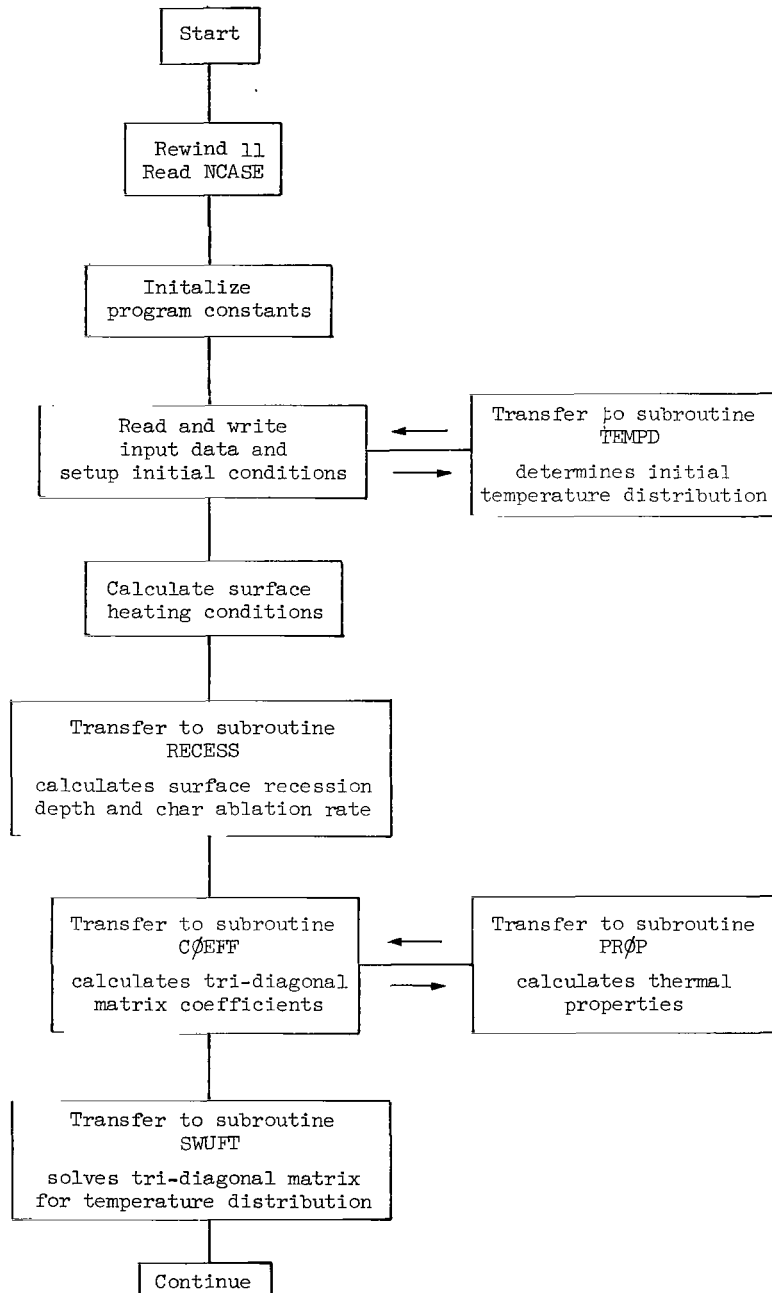
<u>FORTTRAN</u>	<u>Description</u>
SAVY3X	depth of 1060 isotherm at maximum 1460 isotherm depth
SAVY4X	term that will contain maximum depth of 1460 isotherm
SR	surface recession values in surface recession table
T	present time
TABL	temperature at which ablation starts
TCHAR	temperature at which ablation stops
TCP	temperature values in backup material specific heat tables
TCPC	temperature values in char specific heat table
TCPV	temperature values in virgin specific heat table
TEM DI	arbitrary initial temperature distribution values
TEMPI	constant initial temperature distribution value
TENV	interior cabin temperature
TEST2	test to determine proper heat shield initial temperature distribution
TDMP	time to start dumping or printing information used in checkout of program (sets DMP = 1.0)
TIME	trajectory table time values
TINT	starting time of problem
TITLE	control card used for reading in new data for successive problems
TKC	temperature values in char thermal conductivity table
TKV	temperature values in virgin thermal conductivity table
TL	total thickness of heat shield structure (VL + BL)
TLIM	time limit of problem
TREC	surface temperature or time at which char removal is to start
TS	temperature or time values in surface recession table
TTABLE	time values in time-step table

<u>FORTTRAN</u>	<u>Description</u>
TTUL	equals TUL if VPT = 0 or equals TX2 if VPT = 1 - used in computing char properties
TUL	maximum value of TX1 and TX2
TUL1	maximum TX1 values - used in computing gas ablation rate
TUL2	maximum TX2 values - used in computing gas ablation rate
TV	sink temperature of external environment
TW	temperature values in enthalpy table
TX1	temperature of nodes at past time step
TX2	temperature of nodes at present time step
TX2C	temperature at fixed locations in ablation material as defined by XC
TX2T	temporary storage of TX2 temperatures for computing thermal properties
TXK	temperature values in backup material thermal conductivity tables
TXØ	initial temperature at front surface of heat shield for computing linear temperature gradient
TY	temperature distribution at forward time step
VEL	trajectory table velocity values
VELX	trajectory velocity at present time step
VL	initial virgin material thickness
VLI	initial ablation material thickness
VLTEM	value of 1060 isotherm depth from previous time step
VLV	variable ablation material thickness
VPT	test to determine if properties are irreversible with temperature
WEKEEP	depth of 1460 isotherm at any time
XBM	thickness of individual materials in backup
XC	fixed location of nodes in the ablation material
XI	node number

<u>FORTTRAN</u>	<u>Description</u>
XIDNT	any 72 alphanumeric characters to identify each material
XK	thermal conductivity values in backup material thermal conductivity table
XKB	thermal conductivity of backup material node
XKC	thermal conductivity in char thermal conductivity table
XKV	thermal conductivity value in virgin thermal conductivity table
XLØST	amount of solid ablation material lost in a time step due to surface movement
XLSTI	distance from original surface to present front surface location, inches
XLSTV	distance from original surface to present front surface location, feet
XMDC	mass loss rate of char
XMDG	mass gas ablation rate due to pyrolysis of virgin material
XMDØ	mass flux rate of oxygen to surface
XMDT	total ablation rate
XNP	number of nodes in ablation material
XNPM	number of nodes per backup material
XPLØT	time to be written on tape and plotted
XV	location of nodes in variable ablation material thickness
YK	thermal conductivity of a node in ablation material
YPLØT1	recession depth to be written on tape and plotted
YPLØT2	bondline temperature to be written on tape and plotted
YPLØT3	1060 isotherm depth to be written on tape and plotted
YPLØT4	1460 isotherm depth to be written on tape and plotted
ZZZ	ratio to determine when the limiting value of heat blockage has been reached

APPENDIX E

GENERAL FLOW CHART



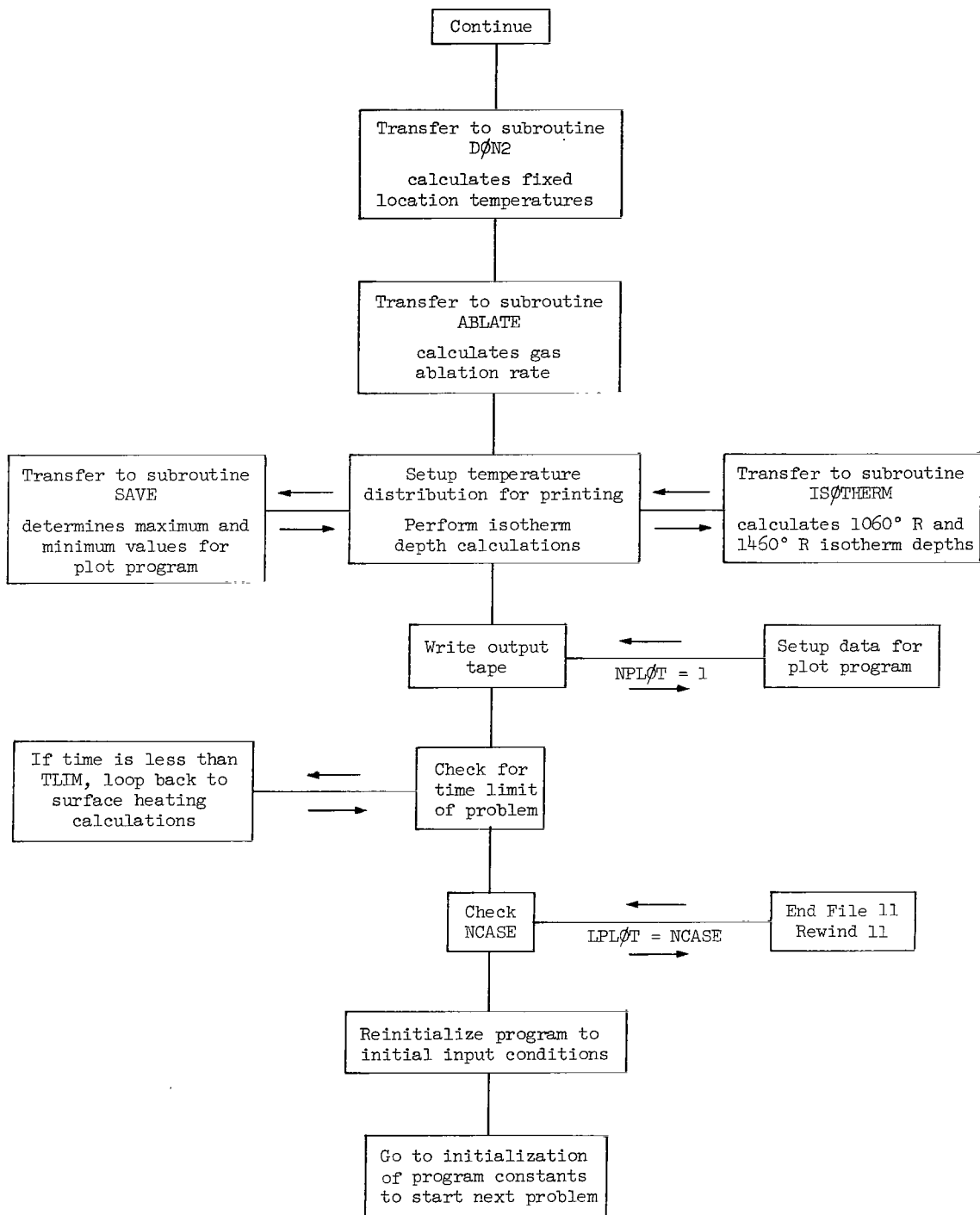


TABLE I.- SAMPLE PROBLEM INPUT

(a) Coding sheet

STATEMENT NUMBER	CONTINUATION																														FORTRAN STATEMENT																				SEQUENCE
LOCATION	OPERATION										VARIABLE FIELD																				COMMENTS																				
1																															TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65 DONALD M. CURRY																				

MSC Form 244 (Apr 1962)

NOTE: WRITE NUMBERS 10, LETTERS I Ø UGZC, SYMBOLS /, *,

TABLE I.- SAMPLE PROBLEM INPUT - Continued

(a) Coding sheet

STATEMENT NUMBER		CONTINUATION		FORTRAN STATEMENT																																	SEQUENCE		
LOCATION		OPERATION		VARIABLE FIELD																				COMMENTS											SEQUENCE				
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80																																							
+600.0		+00		+95.0		+00		+0.0		+00		+2.925		+04																									
1		3		+0.1		+00																																	
+3.0		+00																																					
9		2																																					
BACKUP MATERIAL				0.1 INCHES THICK																																			
+360.0		+00		+0.065		+00		+460.0		+00		+0.065		+00		+560.0		+00		+0.0655		+00																	
+660.0		+00		+0.066		+00		+760.0		+00		+0.0672		+00		+860.0		+00		+0.0684		+00																	
+960.0		+00		+0.069		+00		+1060.0		+00		+0.07		+00		+1160.0		+00		+0.07		+00																	
+360.0		+00		+0.43		+00		+1100.0		+00		+0.43		+00																									
+34.0		+00		+0.1		+00		+0.9		+00		+0.9		+00																									
+0.0		+00		+0.0		+00		+0.0		+00		+0.0		+00																									
HEAT TRANSFER TO CABIN ENVIRONMENT				- HENV=0.0																																			
+560.0		+00		+0.0		+00		+0.0		+00		+0.0		+00																									
INITIAL TEMPERATURE IS CONSTANT																																							
+0.0		+00		+530.0		+00		+530.0		+00																													
42																																							
+0.0		+00		+0.0		+00		+342.9		+00		+1400.0		+00		+449.7		+00		+1800.0		+00																	
+617.2		+00		+2400.0		+00		+791.0		+00		+3000.0		+00		+978.0		+00		+3600.0		+00																	
+1113.0		+00		+4000.0		+00		+1200.0		+00		+4224.0		+00		+1300.0		+00		+4486.0		+00																	
+1400.0		+00		+4723.0		+00		+1500.0		+00		+4936.0		+00		+1600.0		+00		+5127.0		+00																	
+1700.0		+00		+5299.0		+00		+1800.0		+00		+5454.0		+00		+1900.0		+00		+5596.0		+00																	

MSC Form 244 (Apr 1962)

NOTE: WRITE NUMBERS 10, LETTERS I O U G Z C, SYMBOLS / . * *

(a) Coding sheet

3537-64

TABLE I.- SAMPLE PROBLEM INPUT

(b) Fortran data card listing

```

1
TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65      DONALD M. CURRY

+600.0 +00 +0.0 +00 2 1
+0.0 +00 +0.1 +00 100
+600.0 +00 +0.1 +00 100

+1.0 +00 +1.0 +00

TYPICAL CHARRING ABLATION MATERIAL PROPERTIES
+1060.0 +00 +1460.0 +00 +0.0 +00 +34.0 +00 +20.0 +00 +0.00 +00
+0.65 +00 +0.75 +00 +129.06 +00 +1.50 +00 +250.0 +00 +0.0 +00
+1.0 +00 +0.0 +00 +0.12 +00 +0.43 +00 +0.070 +00 +0.43 +00
31 2 2 2
+1460.0 +00 +0.12 +00 +1.0 +04 +0.12 +00
+1460.0 +00 +0.43 +00 +1.0 +04 +0.43 +00
+360.0 +00 +0.065 +00 +460.0 +00 +0.065 +00 +560.0 +00 +0.0655 +00
+660.0 +00 +0.066 +00 +760.0 +00 +0.0672 +00 +860.0 +00 +0.0684 +00
+960.0 +00 +0.069 +00 +1060.0 +00 +0.070 +00 +1160.0 +00 +0.070 +00
+360.0 +00 +0.43 +00 +1100.0 +00 +0.43 +00
+0.0 +00 +9.0 -04 +600.0 +00 +9.0 -04

NO TRAJECTORY - Q=95 RTU/SEC-SOFT
2
+0.0 +00 +45.0 +00 +0.0 +00 +2.925 +04
+600.0 +00 +45.0 +00 +0.0 +00 +2.925 +04

1 3 +0.1 +00
+3.0 +00
9 2
BACKUP MATERIAL 0.1 INCHES THICK
+360.0 +00 +0.065 +00 +460.0 +00 +0.065 +00 +560.0 +00 +0.0655 +00
+660.0 +00 +0.066 +00 +760.0 +00 +0.0672 +00 +860.0 +00 +0.0684 +00
+960.0 +00 +0.069 +00 +1060.0 +00 +0.07 +00 +1160.0 +00 +0.07 +00
+360.0 +00 +0.43 +00 +1100.0 +00 +0.43 +00
+34.0 +00 +0.1 +00 +0.9 +00 +0.9 +00
+0.0 +00 +0.0 +00 +0.0 +00 +0.0 +00

HEAT TRANSFER TO CAPIN ENVIRONMENT - HENV=0.0
+560.0 +00 +0.0 +00 +0.0 +00 +0.0 +00

INITIAL TEMPERATURE IS CONSTANT
+0.0 +00 +530.0 +00 +530.0 +00

42
+0.0 +00 +0.0 +00 +342.4 +00 +1400.0 +00 +449.7 +00 +1800.0 +00
+617.2 +00 +2400.0 +00 +791.0 +00 +3000.0 +00 +978.0 +00 +3600.0 +00
+1113.0 +00 +4000.0 +00 +1200.0 +00 +4224.0 +00 +1300.0 +00 +4486.0 +00
+1400.0 +00 +4725.0 +00 +1500.0 +00 +4936.0 +00 +1600.0 +00 +5127.0 +00
+1700.0 +00 +5299.0 +00 +1800.0 +00 +5454.0 +00 +1900.0 +00 +5596.0 +00
+2000.0 +00 +5728.0 +00 +2100.0 +00 +5851.0 +00 +2200.0 +00 +5968.0 +00
+2300.0 +00 +6078.0 +00 +2400.0 +00 +6186.0 +00 +2500.0 +00 +6291.0 +00
+2600.0 +00 +6395.0 +00 +2700.0 +00 +6497.0 +00 +2800.0 +00 +6597.0 +00
+2900.0 +00 +6699.0 +00 +3000.0 +00 +6805.0 +00 +3100.0 +00 +6918.0 +00

```

TABLE I - SAMPLE PROBLEM INPUT - Concluded

(b) Fortran data card listing

+3200.0	+00+7050.0	+00+3300.0	+00+7175.0	+00+3400.0	+00+7350.0	+00
+3500.0	+00+7480.0	+00+3600.0	+00+7630.0	+00+3700.0	+00+7800.0	+00
+3800.0	+00+7970.0	+00+3900.0	+00+8120.0	+00+4000.0	+00+8300.0	+00
+4100.0	+00+8500.0	+00+4200.0	+00+8700.0	+00+4300.0	+00+8850.0	+00
+4400.0	+00+9000.0	+00+4500.0	+00+9150.0	+00+4600.0	+00+9270.00	+00

TABLE II.- SAMPLE PROBLEM OUTPUT

TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65 DONALD M. CURRY

INPUT DATA.

TIME LIMIT=6.0000E 02 INITIAL TIME=0. NPTT= 2

TIME	TIME STEP	PRINT CONTROL
0.	1.0000E-01	100
6.0000E 02	1.0000E-01	100

FCNNV= 1.0000E 00 FRAD= 1.0000E 00

TYPICAL CHARRING ABLATION MATERIAL PROPERTIES

TABL= 1.0600E 03	TCHAR= 1.4600E 03	TREC= 0.	RHOV= 3.4000E 01	RHOC= 2.0000E 01
FBLW= 0.	EMV= 6.5000E-01	EMC= 7.5000E-01	H300= 1.2906E 02	VL= 1.5000E 00
HV= 2.5000E 02	VPT= 0.	EV= 1.0000E 00	IV= 0.	CHARK= 1.2000E-01
CHARC= 4.3000E-01	ABLK= 7.0000E-02	ABLC= 4.3000E-01		

NP= 31 NKC= 2 NCPC= 2 NKV= 9 NCPV= 2 NREC= 2

VIRGIN MATERIAL

TEMPERATURE	THERMAL CONDUCTIVITY	TEMPERATURE	SPECIFIC HEAT
3.6000E 02	6.5000E-02	3.6000E 02	4.3000E-01
4.6000E 02	6.5000E-02	1.1000E 03	4.3000E-01
5.6000E 02	6.5000E-02		
6.6000E 02	6.6000E-02		
7.6000E 02	6.7200E-02		
8.6000E 02	6.8400E-02		
9.6000E 02	6.9000E-02		
1.0600E 03	7.0000E-02		
1.1600E 03	7.0000E-02		

CHAR MATERIAL

TEMPERATURE	THERMAL CONDUCTIVITY	TEMPERATURE	SPECIFIC HEAT
1.4600E 03	1.2000E-01	1.4600E 03	4.3000E-01
1.0000E 04	1.2000E-01	1.0000E 04	4.3000E-01

SURFACE RECESSION TABLE

TIME	SK - IN/SEC
0.	9.0000E-04
6.0000E 02	9.0000E-04

NO TRAJECTORY - Q=95 BTU/SEC-SQFT

NO. OF TRAJECTORY POINTS = 2

TABLE II.- SAMPLE PROBLEM OUTPUT - Continued

TIME	Q CONVECTIVE	Q RADIATIVE	VELOCITY
0.	7.50000E 01	0.	2.92500E 04
6.00000E 02	9.50000E 01	0.	2.92500E 04

PROPERTIES OF BACKUP STRUCTURE

NO. OF MATERIALS IN BACK-UP SHIELD= 1
 TOTAL NUMBER OF NUDES IN BACK-UP SHIELD= 3
 THICKNESS OF BACK-UP SHIELD= 1.00000E-01

BACKUP MATERIAL 0.1 INCHES THICK

TEMPERATURE	THEMAL	TEMPERATURE	SPECIFIC
	CONDUCTIVITY		HEAT
3.60000E 02	6.50000E-02	3.60000E 02	4.30000E-01
4.60000E 02	6.50000E-02	1.10000E 03	4.30000E-01
5.60000E 02	6.50000E-02		
6.60000E 02	6.60000E-02		
7.60000E 02	6.70000E-02		
8.60000E 02	6.84000E-02		
9.60000E 02	6.90000E-02		
1.06000E 03	7.00000E-02		
1.16000E 03	7.00000E-02		

MATERIAL	DENSITY	THICKNESS	EMISSIVITY		NODES/MATERIAL
			FRONT	BACK	
1	3.4000E 01	1.0000E-01	9.0000E-01	9.0000E-01	3.0000E 00

ADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP STRUCTURE

MATERIAL	FILM COEFFICIENT	GAP THICKNESS	FTEST	BTEST
1	0.	0.	0.	0.

HEAT TRANSFER TO CAVIN ENVIRONMENT - HENV=0.0

TEMPERATURE= 5.60000E 02 FILM COEFFICIENT= 0. VIEW FACTOR= 0. Q LOST= 0.

INITIAL TEMPERATURE IS CONSTANT

TEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM AND EQUAL TO 5.3000E 02

TABLE II.- SAMPLE PROBLEM OUTPUT - Concluded

OUTPUT DATA.

TIME= 9.90000E 00 QCONVECTIVE= 9.50000E 01 GRADIATIVE= 0. VELOCITY= 2.92500E 04
 GAS ABLATION RATE= 0. CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 5.40000E 00
 RECESSION DEPTH= 9.00000E-03 QHOT WALL= 8.99282E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 1.00000E 01 SECONDS

TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

3.79022E 03	2.33046E 03	1.06300E 03	6.38075E 02	5.47600E 02	5.32434E 02
5.30289E 02	5.30030E 02	5.30002E 02	5.30000E 02	5.30000E 02	5.30000E 02
5.30000E 02	5.30000E 02	5.29999E 02	5.30000E 02	5.30000E 02	5.30000E 02
5.30000E 02	5.30000E 02	5.30000E 02	5.30000E 02	5.30000E 02	5.30000E 02
5.30000E 02	5.30000E 02	5.30000E 02	5.29999E 02	5.30000E 02	5.30000E 02
5.29999E 02					

TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

5.29999E 02 5.30000E 02 5.30000E 02

TIME= 1.99000E 01 QCONVECTIVE= 9.50000E 01 GRADIATIVE= 0. VELOCITY= 2.92500E 04
 GAS ABLATION RATE= 2.90720E 01 CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 3.44720E 01
 RECESSION DEPTH= 1.80000E-02 QHOT WALL= 8.99173E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 2.00000E 01 SECONDS

TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

3.80935E 03	2.87678E 03	1.64575E 03	9.77202E 02	6.72698E 02	5.66204E 02
5.37857E 02	5.31496E 02	5.30254E 02	5.30038E 02	5.30005E 02	5.30000E 02
5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02
5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02
5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02
5.29999E 02					

TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

5.29999E 02 5.29999E 02 5.29999E 02

TIME= 2.99000E 01 QCONVECTIVE= 9.50000E 01 GRADIATIVE= 0. VELOCITY= 2.92500E 04
 GAS ABLATION RATE= 1.25330E 01 CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 1.79330E 01
 RECESSION DEPTH= 2.70000E-02 QHOT WALL= 8.98427E 01

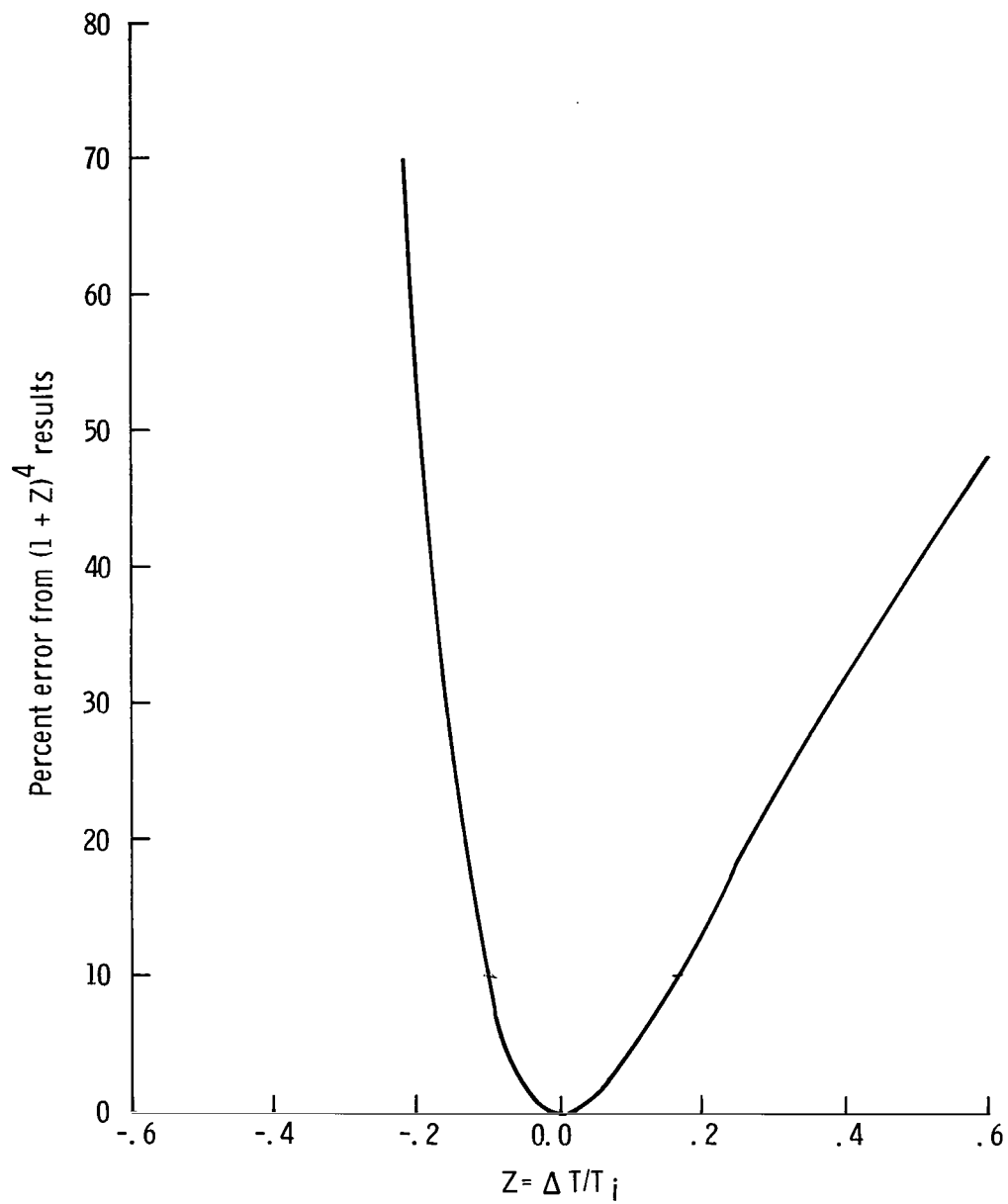


Figure 1. - Radiation temperature approximation error.

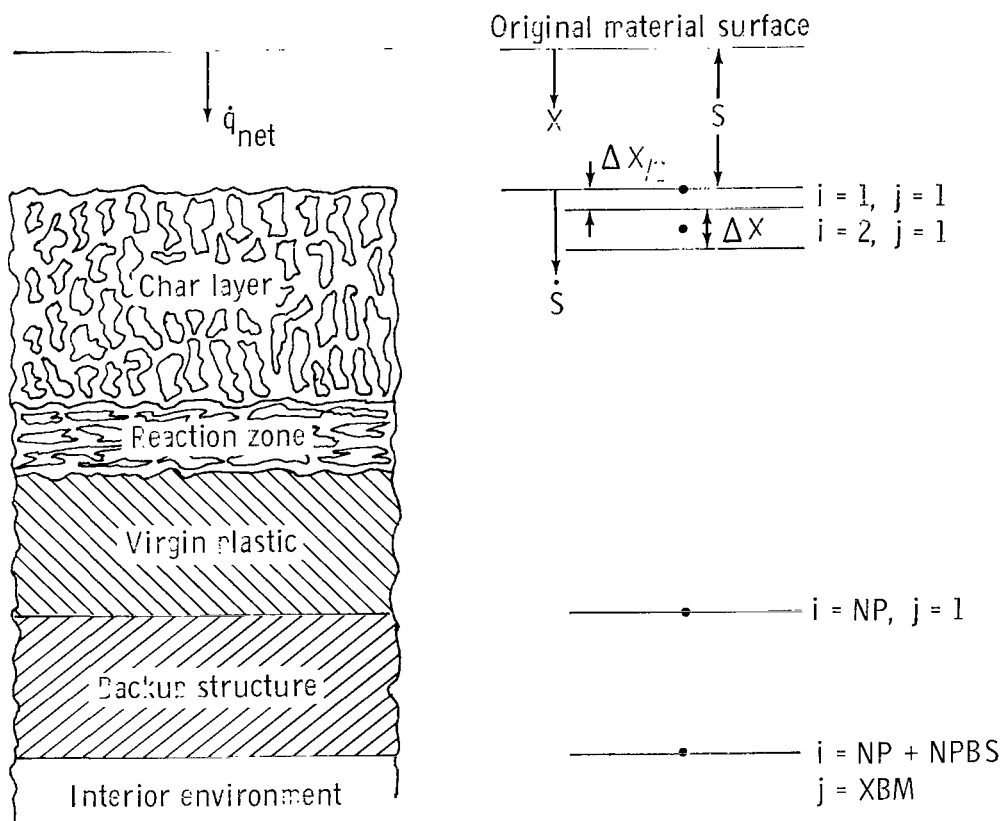


Figure 2. - Schematic diagram of charring ablator thermal protection system.

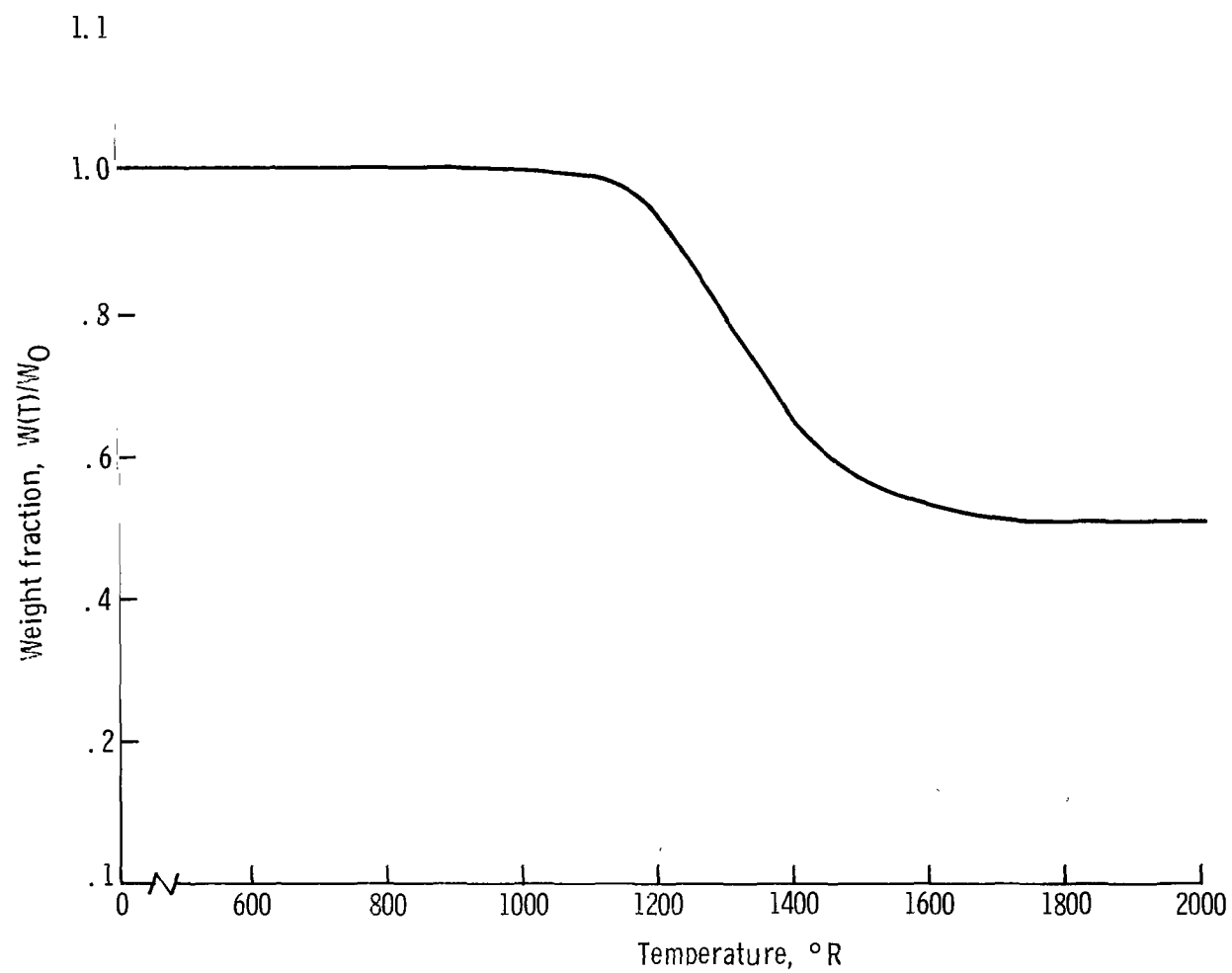


Figure 3. - Thermogravimetric data for typical charring ablation material.

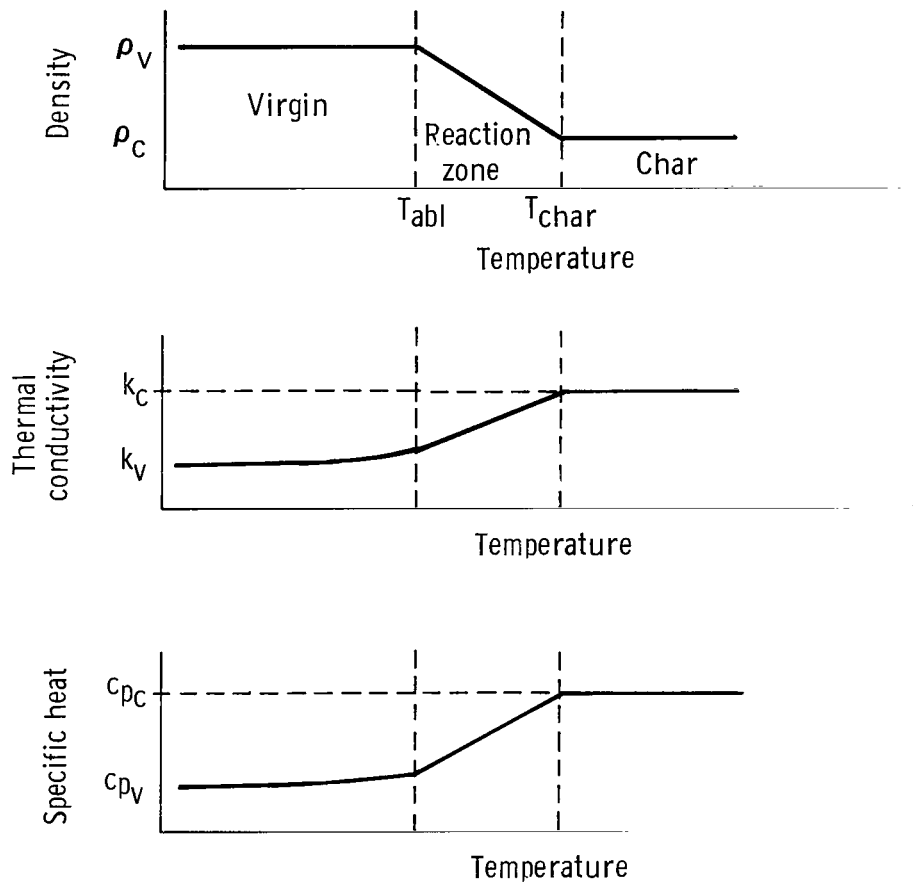


Figure 4. - Charring material property variation used as input to STAB II.

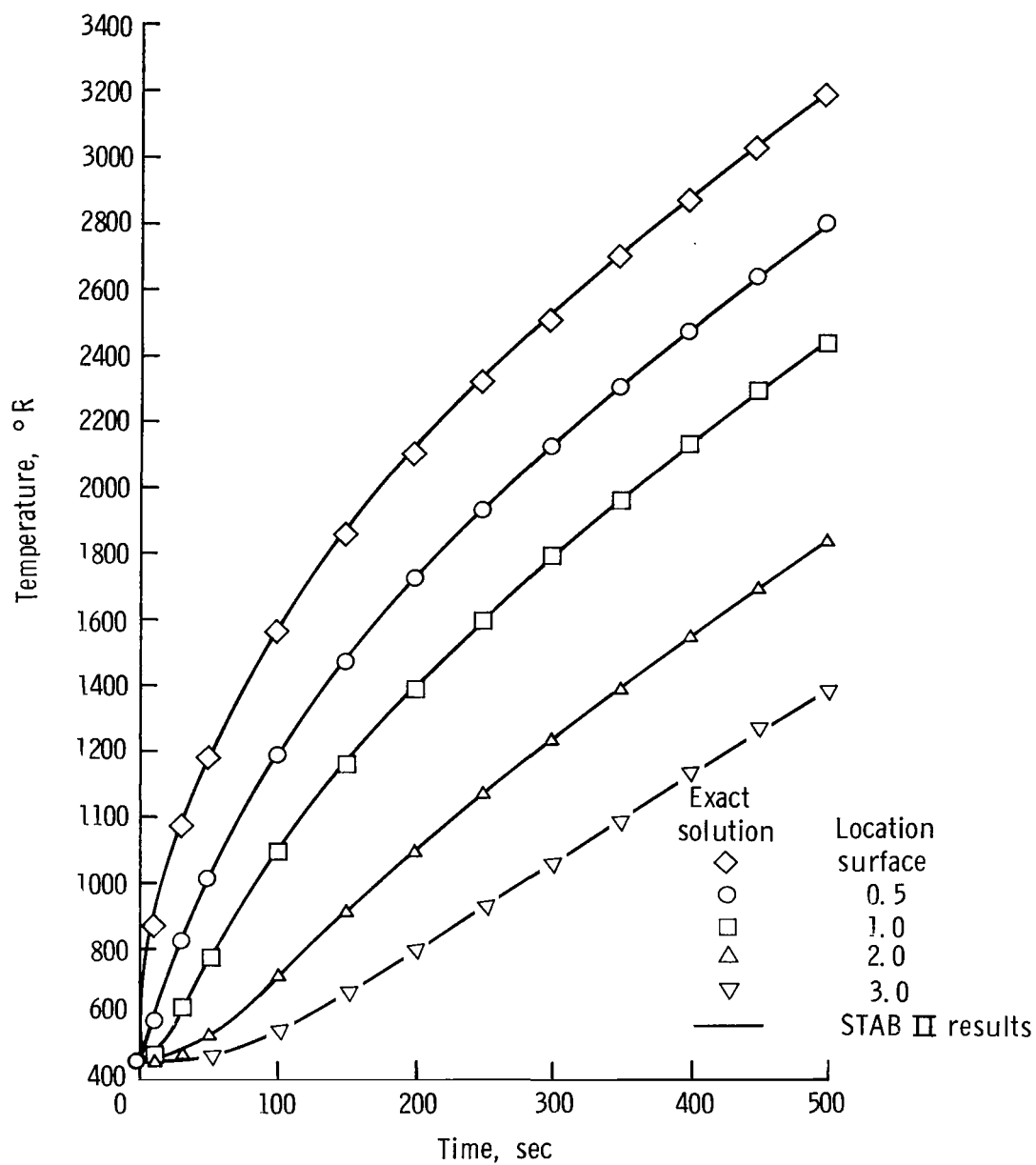


Figure 5. - Comparison of temperature histories for nonablating steel slab (pure conduction)

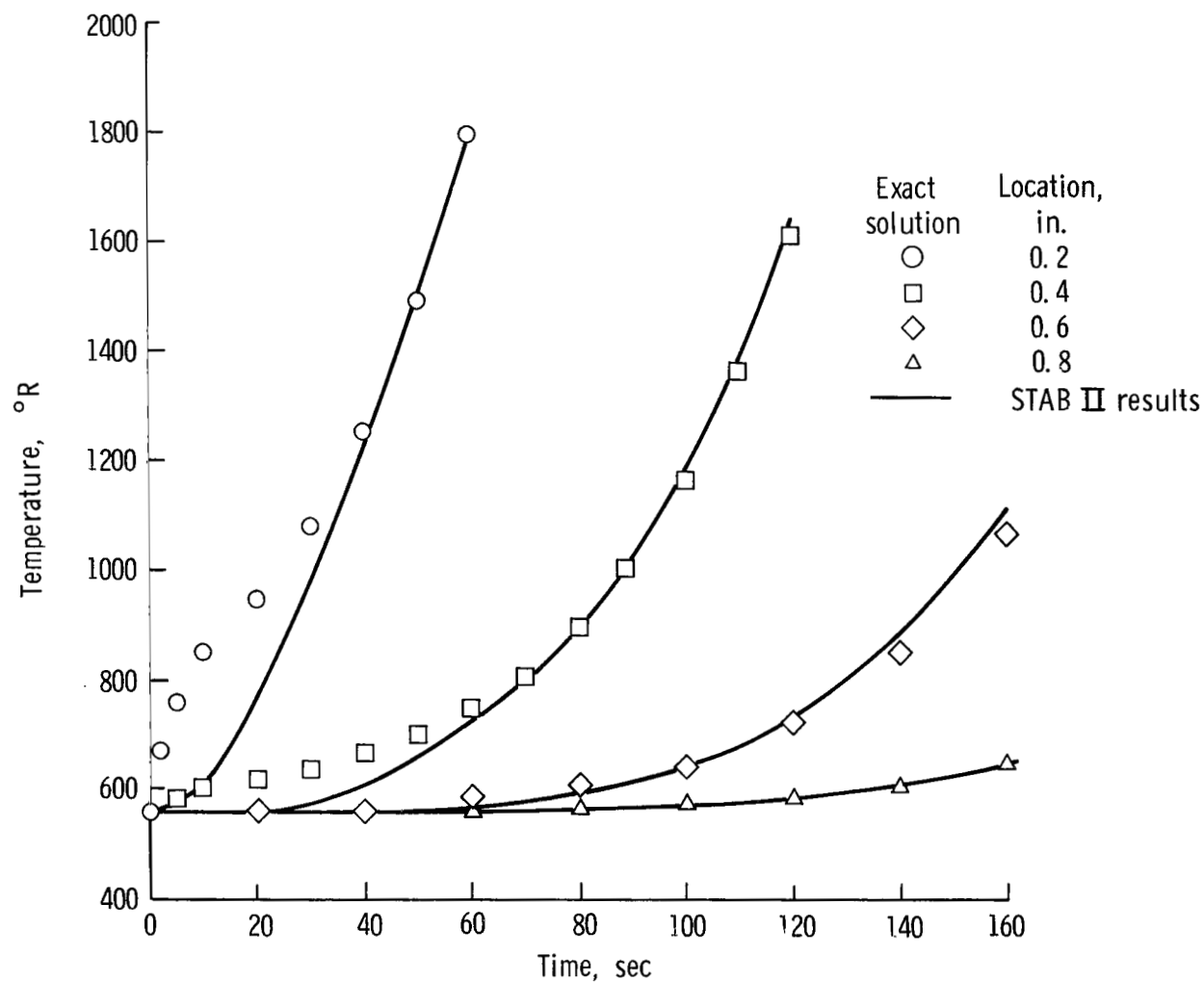


Figure 6. - Comparison of temperature histories for moving boundary model.

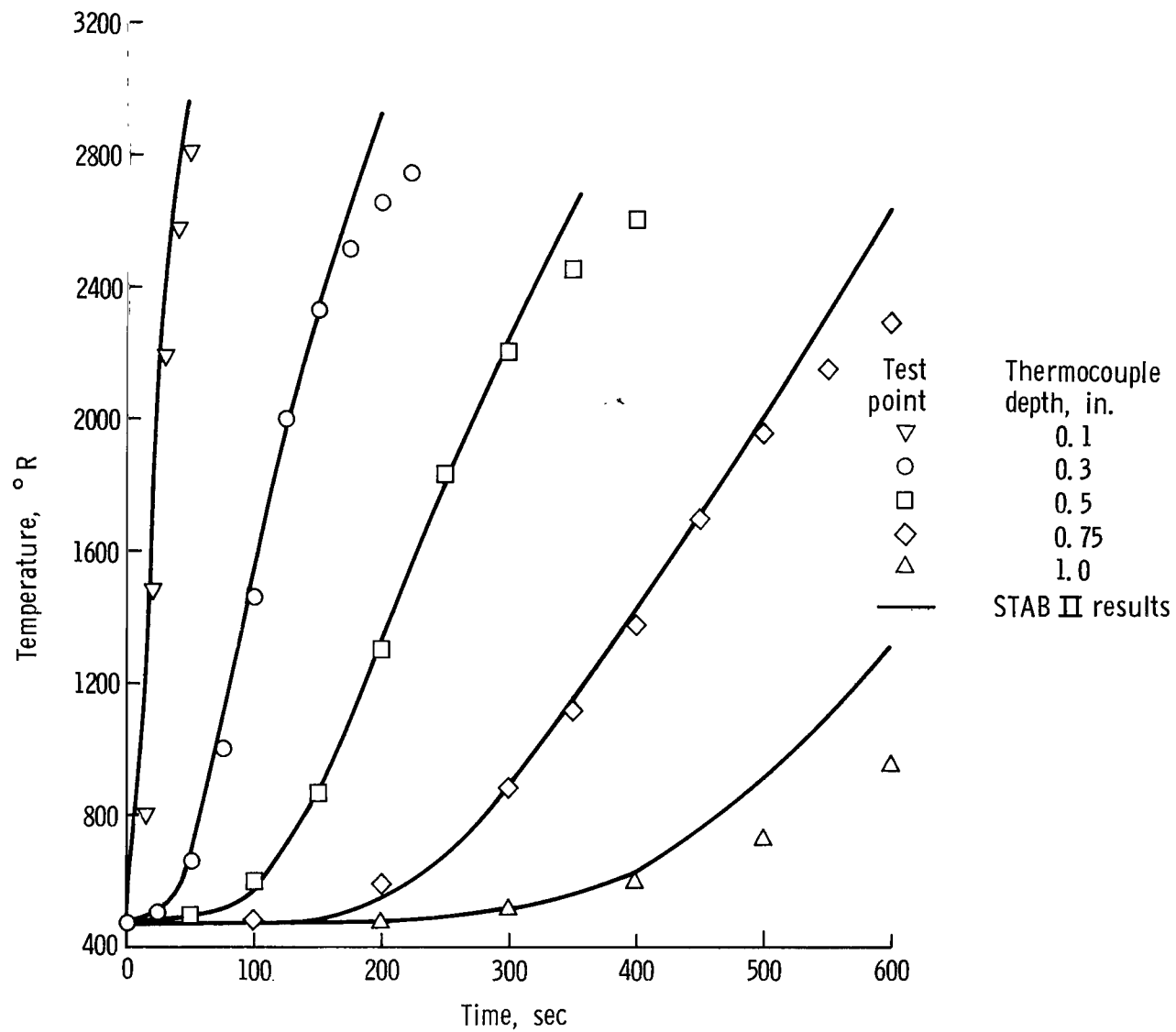


Figure 7. - Comparison of temperature histories for typical charring ablator.

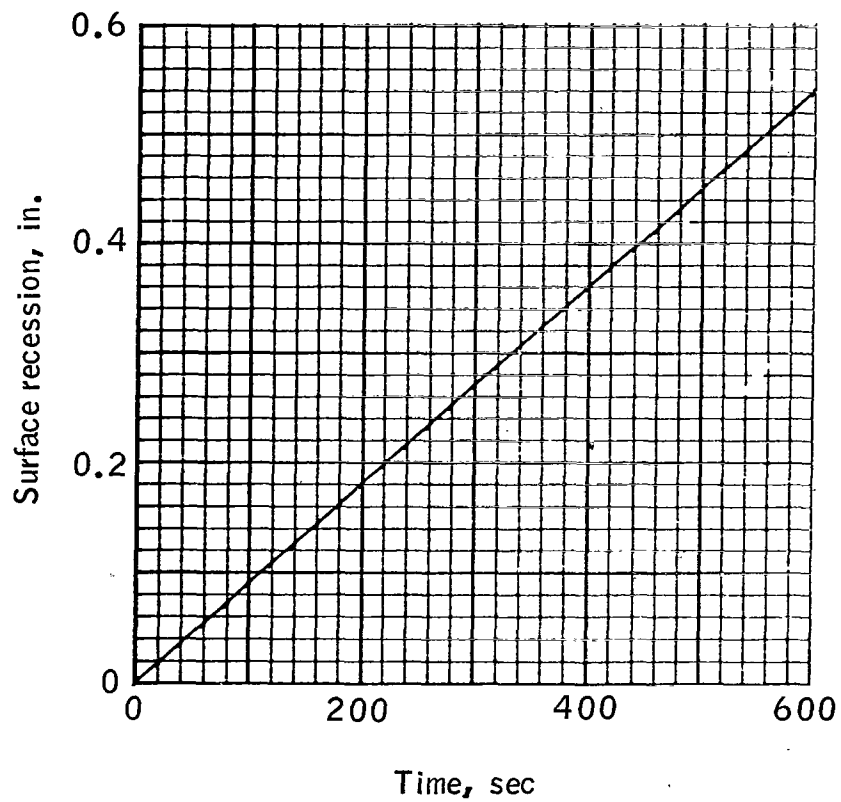


Figure 8. - Plot program surface recession curve from typical charring ablator test case.

Recession depth

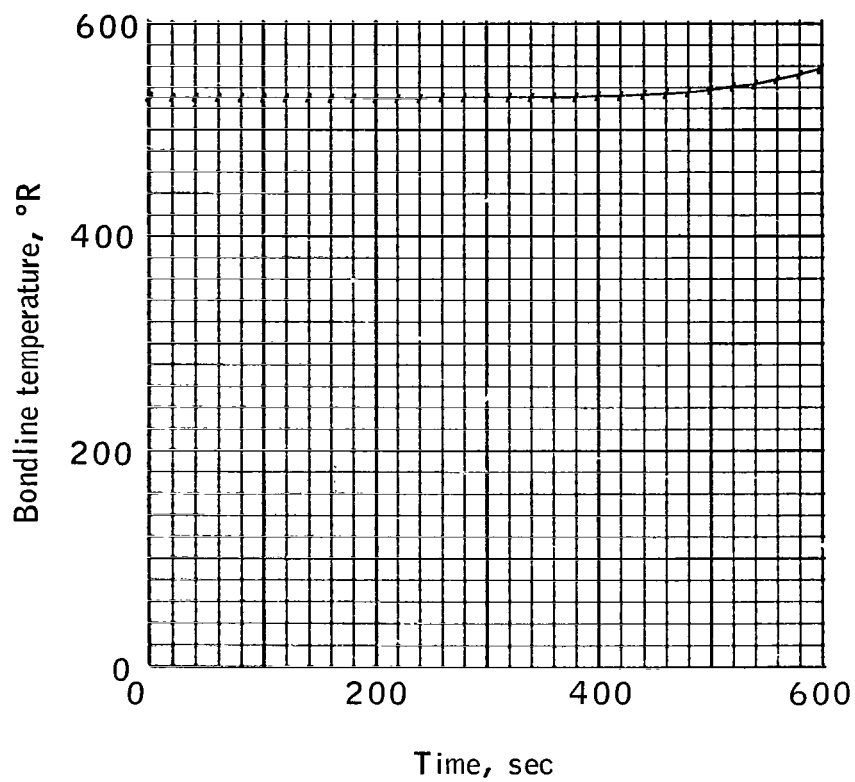


Figure 9. - Plot program bondline temperature curve from typical charring ablator test case.

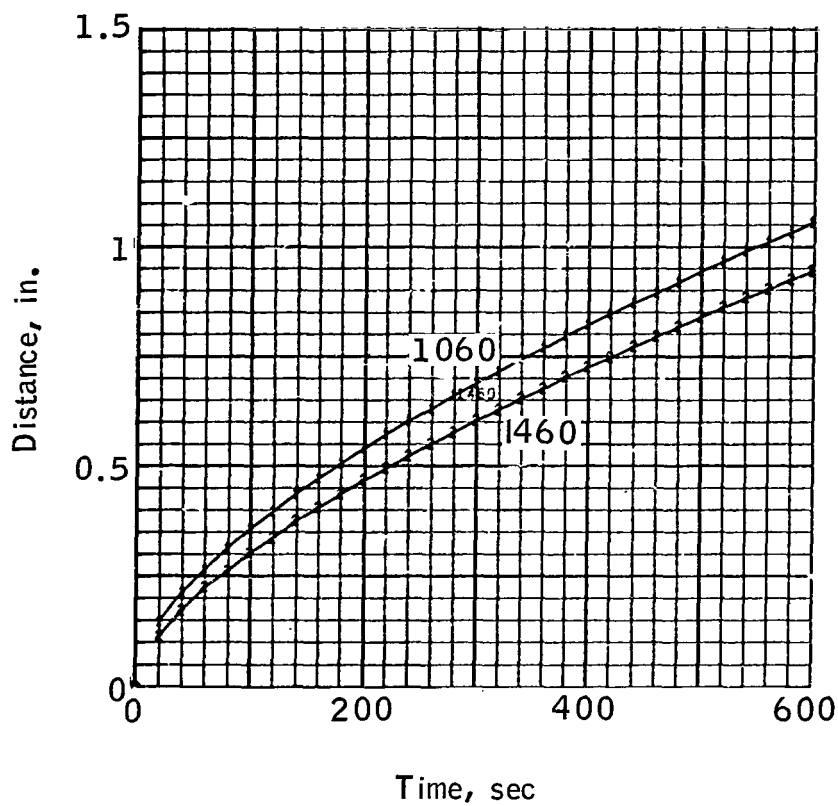


Figure 10. -Plot program 1060°R and 1460°R isotherm curves from typical charring ablator test case.

3/22/82

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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